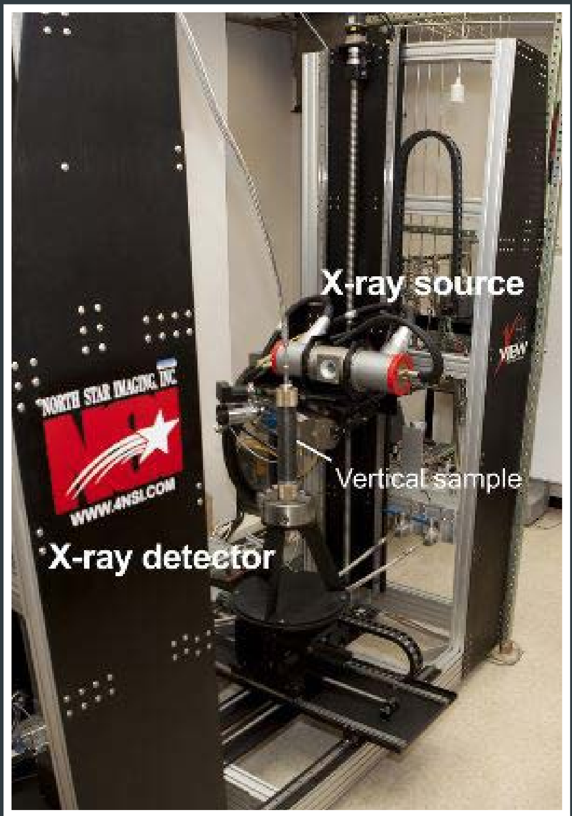
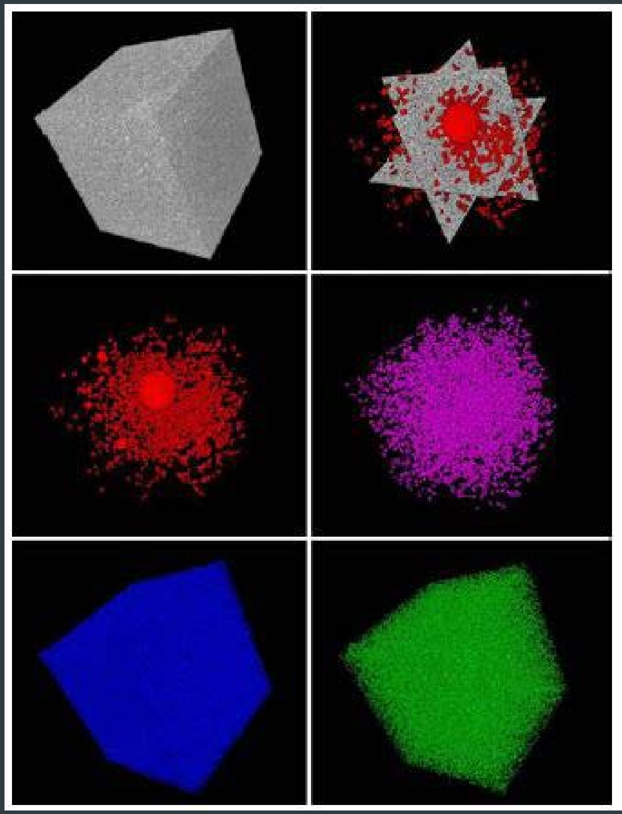
NATIONAL ENERGY TECHNOLOGY LABORATORY

# Research Portfolio Report



*Ultra-Deepwater: Drilling and Completion Operations*

U.S. DEPARTMENT OF ENERGY

**Cover images:** **Photograph of the North Star Imaging M-5000 industrial CT scanner (left) and 3-D renderings of a (10.4 mm)$^3$ digital subsection of 10% foam quality cement sample (right).**

# Research Portfolio Report

## Ultra-Deepwater:
## Drilling and Completion Operations

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**DOE/NETL-2015/1697**

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**Contract DE-FE0004003**
**Activity 4003.200.03**

# DISCLAIMER

# ACKNOWLEDGEMENTS

The authors would like to express appreciation to all the individuals who contributed to this project and the preparation of this report, including Karl Lang of Leonardo Technologies, Inc. The authors thank the reviewers, including James Pappas [Research Partnership to Secure Energy for America (RPSEA)], Roy Long (NETL), James Ammer (NETL), John Oelfke (KeyLogic Systems, Inc.), and William Schuller (AECOM); their constructive comments are greatly appreciated. The authors would also like to thank the numerous industry technology developers and practitioners who developed the technology, conducted field tests, and attempted to expand the application of the technology to wider applications. This work was funded by the U.S. Department of Energy Office of Fossil Energy through the National Energy Technology Laboratory.

The project data, photos, and graphics provided in the project summaries that follow the introduction come from available project documentation—including final reports, fact sheets, NETL project summaries, RPSEA monthly reports, and project websites—and through the generous assistance of Principal Investigators, industry partners, RPSEA, and NETL staff.


**Image caption:** *NETL lead researcher Barbara Kutchko does subsurface work in one of NETL's experimental facilities.*

## Executive Summary

The Energy Policy Act of 2005 called for an Ultra-Deepwater (UDW) and Unconventional Oil and Natural Gas R&D program that also included a focus on helping small oil and gas producers. The UDW portion of the research was initially focused mainly on the production challenges as producers continued to develop resources in water depths in excess of 10,000 feet, which pushes the limits of industry state of the art. This portfolio focus was changed to one of safety and environmental sustainability following the April 20, 2010, blowout on The Deepwater Horizon, Transocean's drilling platform on British Petroleum's (BP's) Macondo development, which killed 11 workers.

***DOE creates and supports partnerships that drive the development of new ultra-deepwater technologies, data sets, and methodologies.***

Results from the many committee meetings and hearings that followed Macondo reinforced the idea that better technologies will be required to enhance risk reduction in both operations and facilities in the UDW environment. Since many of the facilities in UDW include subsea systems that will operate autonomously on the ocean floor, a separate focus on the reliability of the components within these complex production systems was included. An additional concern was uncertainty regarding the potential to drill into geologic hazards, which remains very high for all exploratory drilling. The term "wellbore stability" was added to surface systems in recognition that the wellbore in UDW now included an engineered system from the ocean floor, supported by the drilling platform, which undergoes continual stresses and corrosion during drilling. In order to ensure wellbore integrity throughout the well, analysis of cumulative fatigue in that system must be accounted for in design and maintenance.

By definition UDW (i.e., 5,000 or more feet of water depth) is one of the areas of the world where potentially significant oil and natural gas resources remain to be discovered and produced. Producing systems employed to extract oil and gas from UDW areas include floating facilities (surface systems) as well as subsea trees, other subsea production equipment, and the flowline and power components that connect elements on the seafloor (umbilicals) and connect the seafloor assemblage with the surface facility (risers). The Drilling and Completion Operations research bin aims to improve resource estimates, reduce hydrocarbon exploration uncertainties, minimize the drilling of unnecessary wells, develop environmentally friendly alternatives to marine seismic shooting, identify shallow drilling hazards through better pressure prediction, and identify deep, over-pressured or under-pressured reservoirs before encountering them.

The overarching goal of the UDW R&D portfolio is to "ensure that the understanding of the risks associated with ultra-deepwater operations and associated mitigation methods keep pace with the technologies that industry has developed to tap reserves in increasingly challenging conditions." Because of the potential for environmental impacts to marine life and coastal communities, UDW research must develop inherently safer surface and subsurface designs to reduce the risks of accessing UDW oil and natural gas resources, while expanding the capabilities of facilities and other equipment. Specific to these challenges is the need for enhanced topsides facilities, improved hulls, stronger moorings and risers; advanced subsurface tools and monitoring equipment; improved modeling tools for safer vessel designs from explosion hazards and violent sea events; as well as the development of "next generation" metocean and meteorological predictive techniques – all with the goal of reducing or eliminating risks and uncertainties and increasing the likelihood of seamless operation under a wide range of environmental conditions.

DOE's National Energy Technology Laboratory (NETL), RPSEA, and industry and academic partners continue to carry out research into technologies that can reduce the chances of environmental impacts from ultra-deepwater production activities. This effort includes research funded through Section 999 of the Energy Policy Act of 2005 (Section 999) which directed that royalties be used to fund an oil and natural gas R&D effort, the Ultra-Deepwater and Unconventional Natural Gas and Other Petroleum Resources Research Program. This program was designed to focus on technology challenges in three areas: ultra-deepwater production, challenges commonly faced by small producers, and challenges related to "unconventional natural gas and other petroleum resource exploration and production technology." A key part of this program has been developing technologies to reduce or mitigate environmental impacts associated with production in all three areas.

Drilling and completion operations research carried out by the Department of Energy (DOE) over the past decade has accomplished some significant results that are enhancing our ability to advance ultra-deepwater (UDW) oil and gas development. Among the many accomplishments highlighted in the following pages are examples of how DOE, RPSEA, industry, and academia partnered and:

- Developed an "early warning" drill bit system that can detect conditions just after a drill bit penetrates a formation and triggers flow into the wellbore, but before that flow ascends towards the surface and develops into a potential safety concern;
- Obtained the first CT images of foamed cement systems which allows for the quantitative analysis of physical properties and structures within the cement (particularly bubble sizes and distributions) and developed a reliable methodology to probe the microstructure of foamed cements under in situ conditions; and
- Provided powerful new advances for modeling detailed pressure and stress fields for managed pressure drilling.

## Introduction

The goal of the UDW program is to improve the reliability of conditionally-accessible systems located on the ocean floor, up to 2-¼ miles from the nearest service/control vessel. This research focuses on improving risk management, increasing drilling safety, providing new surface systems components and connecting umbilicals, and developing new inspection platforms, sensors, models, tools, and techniques that improve subsea measurement and system assessment capabilities.

The research projects within the UDW portfolio have been categorized into "bins" of projects that are focused on a common topic. This Research Portfolio Report provides a snapshot of results and accomplishments to-date for active and completed projects in the UDW portfolio that are grouped into the Drilling and Completion Operations bin. The first section of this report provides an overview of the bin. Project summaries for each of the projects that include the objective, research conducted, results, and other pertinent information for each of the projects are provided in the pages that follow.

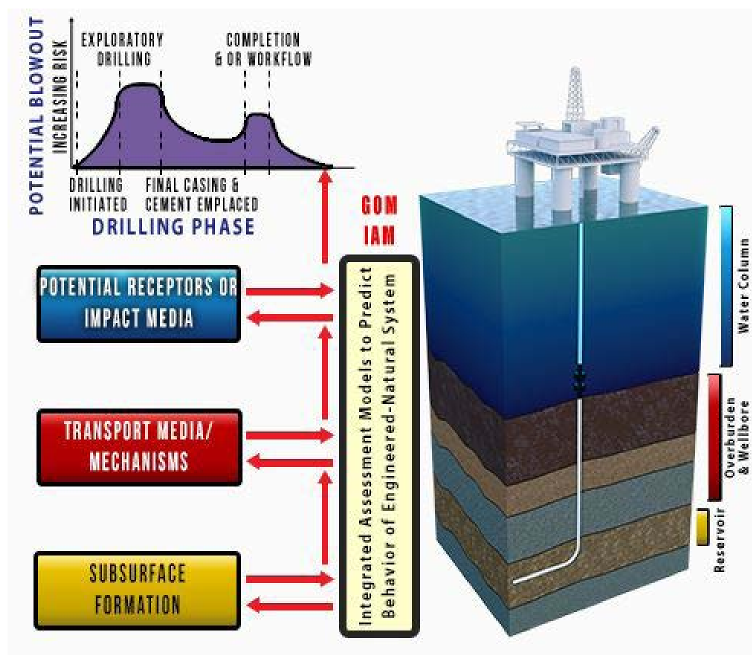


**Image caption:** *NETL's integrated assessment models incorporate data from the water column, the overburden and wellbore region, and the reservoir.*

# What is Drilling and Completion Operations research?

Research focused on drilling and completion operations is often conducted by interdisciplinary teams of scientists and engineers from the oil and gas industry service sector, producers, and academia. For these research projects, cross-cutting research and development (R&D) efforts capitalize on the strengths of the interdisciplinary teams and combines laboratory-based experiments with the development and integration of field-based datasets and numerical simulators. As a result, they develop the scientific basis necessary for assessing, reducing, and quantifying potential risks, as well as designing equipment and drilling specifications and providing science-based prediction methods that will allow rapid responses and successful mediation of potential hazards associated with exploration and production in offshore environments.

# Why conduct this research?

Drilling and completion operations research increases our understanding of UDW subsurface well conditions, which leads to more accurate and effective drilling and completion methods, guidelines, and tools. Accurate real-time monitoring of reservoir fluids (pressures, fluid type, flow rates, and temperatures), changing conditions during cementing operations, and conditions during subsequent servicing of the wells will allow for timely interpretation of data that will help recognize dangers. New technologies, such as the development and placement of measuring instruments in wells, will provide real-time information on subsurface conditions. New materials and new information on existing materials—for instance, the most appropriate drilling fluids and corrosion-resistant pipe—will make drilling inherently safer. NETL's drilling and completion operations research provides necessary reliable information on conditions at all points within the well during drilling, completion, and production activities that can act to reduce the probability of loss of well control.

# Accomplishments

Accomplishments from drilling and completion operations projects contribute to safety and environmental sustainability and improve the understanding of the UDW subsurface environment. Some of the projects in the Drilling and Completion Operations bin are already completed; therefore, the project deliverables have already been submitted.

## Advanced Steady-State and Transient, Three-Dimensional, Single and Multiphase, Non-Newtonian Simulation System for Managed Pressure Drilling

The objective of this project was to accurately model flow in highly eccentric borehole annular cross-sections typical of modern deviated and horizontal wells. The researchers solved the challenges inherent in modeling these highly complex drilling system configurations using analytical and numerical methods.

The fast, extremely stable numerical methods were hosted by user-friendly, "plain English" graphical interfaces (with integrated 3D color capabilities) that support job planning efforts and particularly on-site field use. An open source program was created to perform the model simulations. As a result new advances were made in modeling detailed pressure and stress fields in general borehole flows, which has led to many "firsts."

For example, this model rigorously calculates plug zone size, shape and location for arbitrary annular cross-sections; accounts for detailed hole geometry and rheology in swab-surge analysis; enables more representative hole cleaning correlations ; and incorporates extremely fast and stable real-time methods for "cement displacing mud" applications that can be conveniently run at the rig site.

Additional details on this project are available on **p. 20.**

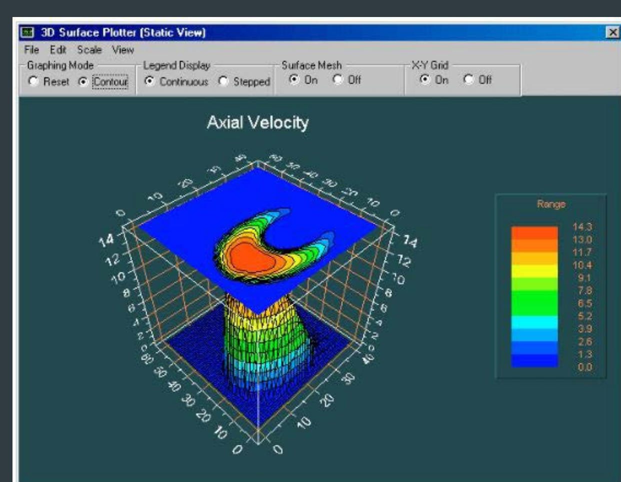


**Image caption:** *"Static 3D" display with contour plot generation.*

The following selected examples of accomplishments recorded by these research projects illustrate how they are influencing drilling and completion:

- *Coil Tubing Drilling and Intervention Systems Using Cost Effective Vessel*

  Research conducted by Nautilus International, LLC led to the design of supporting equipment for a sophisticated Self-Standing Riser (SSR) to support coiled tubing intervention in ultra-deepwater. The riser enables a full performance envelope of coiled tubing abilities. The technology is being field tested on a deepwater satellite well. A successful test will prove that a small vessel can operate coiled tubing through an SSR in deepwater, demonstrate improved safety and environmental protection, and achieve that at a cost less than half that of a Mobile Offshore Drilling Unit. It has the potential to open up many deepwater (1000 to 5000 ft water depth) shallow gas plays (3000 to 12,000 ft depth subsurface) that are currently considered to be noncommercial using conventional deep water technologies. In addition, SSRs can solve the looming challenge of the premature abandonment of hundreds of deepwater wells in the Gulf of Mexico, West Africa, and Brazil that could be re-completed to unproduced zones. Recompletion requires costly use of Mobile Offshore Drilling Units (MODU); the cost is prohibitive, and abandonment leaves thousands of barrels of oil unrecovered.

- *Modeling and Simulation of Managed Pressure Drilling for Improved Design, Risk Assessment, Training and Operations*

  Stratamagnetic Software, LLC generated new and innovative capabilities of modeling fluid flow in highly eccentric annuli of drilling and cementing systems. The work has been published in a new book titled ***Managed Pressure Drilling: Modeling, Strategy and Planning***. Multiple models are covered: steady state and transient flow, 2 and 3-D flow in single and multi-phase fluids, and Newtonian and non-Newtonian rheologies for both drillpipe and eccentric annuli. This book is now in use by the managed pressure drilling industry and is contributing to an increased utilization of the technology.

- *Risk Reduction at the Drill Bit – Adaptation of Existing Technology to Reduce Risk Associated with Deep and Ultra-Deep Drilling*

  NETL's Office of Research and Development (ORD) developed an early detection system for over-pressured formations. The system will be able to detect conditions immediately after the drill bit penetrates a formation that results in a kick, but before that kick ascends to the rig floor. It is a low cost process involving mathematical filtering algorithms required to separate intra-borehole data from logging-while-drilling measurements. This detection system uses standard well logging instrumentation suites; it has received a provisional patent and has been accepted for full patent consideration by NETL's Invention Review Board.

- *Characterizing the Behavior of Metal-Based Systems Used for Control Devices in Extreme Environments*

  NETL ORD investigated the failure mechanisms and rates of failure for critical metal components used in both drilling and well completion activities, including blowout preventers and risers, and drill pipe. Researchers analyzed data sets covering observed and reported behavior in the field, and carried out experimental studies of materials behavior under simulated extreme conditions in the laboratory to

## Intelligent Production System for Ultra Deepwater with Short Hop Wireless Power and Wireless Data Transfer for Lateral Production Control and Optimization

This project sought to develop a safe system that could be deployed in multilateral well completions that would increase the life of the wells while decreasing the production costs. This system would provide remote flow control capabilities inside the laterals using an electric, ultra-low power choke system with real time production data collection capability. It would wirelessly transfer data and power from the main bore to the laterals. Power transfer can also be accomplished from an upper to a lower completion over long distances, so that gauges and flow control modules can be deployed closer to the producing zones along a wellbore.

A full internal diameter flow control system was created and developed that can be placed in wellbore laterals requiring less than one Watt of power to open or close sleeves. A wireless power transfer concept was determined to be feasible at much higher efficiencies than originally conceived and at much longer distances than anticipated. The downhole wireless communications system was also shown to be reliable, capable of two-way data and command transfer, and immune to the downhole environment.

Additional details on this project are available on **p. 23.**

identify and understand how these materials fail. Studies examined corrosion and fatigue of hammer-peened and heat treated alloys, fracture development in drill pipe, and the corrosion degradation of high-strength steels from $H_2S$. The application of these analyses will lead to new technologies and materials to help reduce or eliminate potential catastrophic loss-of-control events. Understanding the behavior of materials under extreme drilling conditions becomes critical to better design and operations.

- *State-of-the-Art Capabilities for Cement Research*

  NETL ORD's multiscale CT imaging facility is equipped to investigate cement properties under in situ conditions that replicate downhole cement environments. To gain an unprecedented view of how foamed cement forms at elevated pressures typical in the subsurface, NETL uses industrial, medical, and micro CT scanners in conjunction with pressure vessels to study in situ cement conditions over a range of pressures and foam qualities. CT scanning and other capabilities housed at the laboratory are helping researchers answer fundamental questions about how cement, casing, and subsurface formations interact downhole.

## What are the benefits of Drilling and Completion Operation research?

NETL carries out drilling and completion operation research to better understand the complex interplay between high-pressure, high-temperature conditions and the performance of drilling and well completion equipment in these environments. NETL has developed cost-effective technologies that can monitor downhole conditions; identified materials that are best suited for subsurface conditions; devised new methods for modeling and managing pressures; and improved cement, telemetry and drilling fluids. NETL's development of databases and models will improve well control and wild well intervention techniques, better monitoring instruments, and the reduction of risks, helping to ensure that hydrocarbons are safely extracted in an environmentally-sound manner. Improved drilling and completion operation techniques and tools can lead to spill prevention, improved safety, and reduced environmental footprint over the life of a field.

## Lessons Learned

As with any type of research, drilling and completion operation research sometimes yields unexpected findings and uncovers challenges that need to be addressed through further research. The following "lessons learned" have been identified in final reports of completed projects.

- *Smart Cementing Materials And Drilling Muds For Real Time Monitoring Of Deepwater Wellbore Enhancement, Phase II*

  Experiments demonstrated that drilling fluid and cement levels can be monitored consistently and effectively by measuring resistance. In addition, changes in their properties and surrounding conditions, such as composition, degree of curing, internal stress, occurrence of cracks, fluid loss characteristics and temperature, can be correlated to resistivity changes to support the monitoring of cement and drilling mud/fluid behavior over time.

- *Deepwater Reverse-Circulation Primary Cementing*

  In Reverse-Circulation Primary Cementing (RCPC) fluids are pumped downhole via the annulus, around the casing shoe and then up into the casing, in contrast to a conventional cement job where fluids are pumped down the casing and up the annulus. This study evaluated the applicability and benefits of RCPC under deepwater conditions on a case-by-case basis. Researchers found that the technology needed for future development includes the modification of float equipment and a switchable crossover that will divert fluids on demand. In addition, tool development should allow for nonmechanical operation of tools from the surface by incorporating technologies such as RFID, chemical-activated triggers, or mudpressure pulses. Mud removal and fluid separation will remain a major challenge for deepwater RCPC since physical separation will need to be maintained through the use of viscous plugs instead of traditional plugs, darts, or balls. Simulation of various wellbore and casing string combinations revealed that the cement slurry is often exposed to a higher downhole circulating temperatures, and that placement time can be shortened significantly in some cases via RCPC. Hydraulic analysis of these deepwater strings has confirmed the critical depths at which placement by RCPC results in a lower equivalent circulating density (ECD).

- *New Safety Barrier Testing Methods*

  Safety barriers are particularly important for ultra-deepwater applications for which the failure to hold, operate, and maintain pressure could have catastrophic impacts to worker safety, the environment, and the economics of well operators. A significant finding of this work is that thermal effects of the well must be accounted for in order to properly interpret pressure results. For example, during testing of a safety valve, where the fluid column in the well had stratified and there was a gas cap at the top, the gas pressure decreased as the gas cooled and as the liquid column cooled and became smaller in volume, expanding the gas volume. The pressure also increased as leaked product entered the column. The interaction of these three activities was shown to be complex, but modeling was used to successfully evaluate the valve integrity under these conditions.

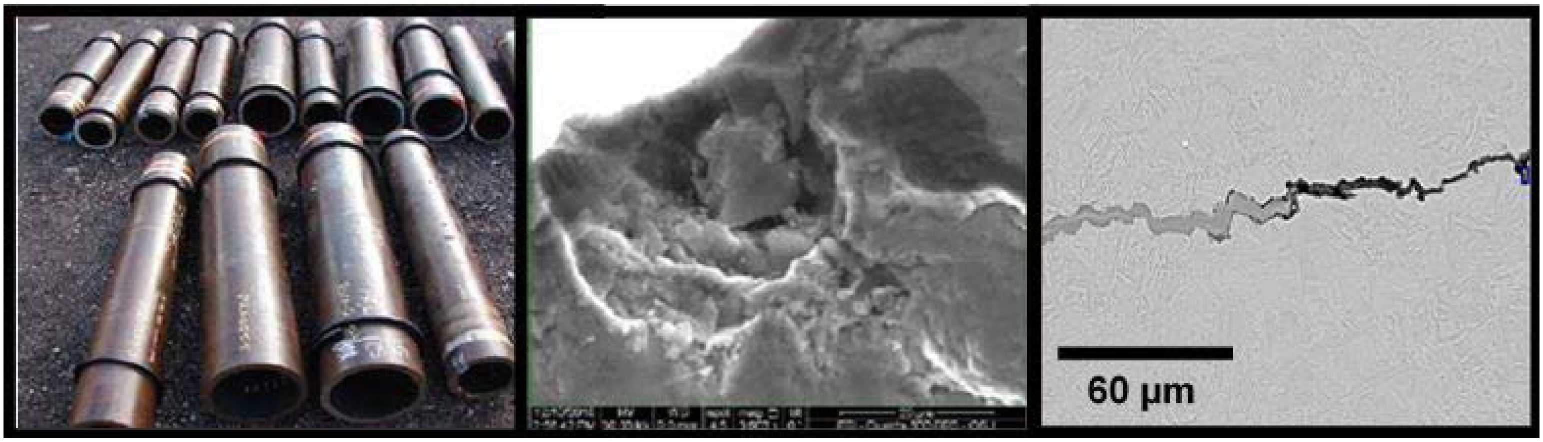


**Image caption:** *NETL is studying corrosion and fatigue performance of high-strength tubulars in seawater and sour brine environments and how conventional alloys, advanced alloys, and surface treatments may allow for safe and reliable use of metallic components in extreme and unproven wellbore conditions.*

## Drilling and Completion Operations Projects

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## Design Investigation of Extreme High Pressure, High Temperature (XHPHT) Subsurface Safety Valves (SSSV)

**Objective:** To investigate ways to enhance SSSV design in the hope of advancing new methods that can be applied to valves subject to pressures of 30,000 psi and temperatures in excess of 400°F.

**Research Conducted:** SSSVs are vital fail safe systems that are used to shut off producing wells before overpressure occurs and results in a catastrophic release of reservoir fluid into the environment. SSSVs have a high rate of failure when used in extreme XHPHT downhole environments. As offshore exploration of oil and gas reserves advances into ultra-deepwater, SSSV technology must be designed to safely withstand these challenging environments. New SSSV technologies are difficult to implement because of a lack of performance history and complex failure modes can go undetected at the design stage. Further, full-scale field testing and validation of XHPHT design concepts are prohibitively expensive, putting an extra burden on the quality of the system modeling.

The project had two main stages. During the first stage, project researchers completed an extensive survey on SSSV technologies, discussed the potential improvement of industry standards on SSSV designs, reviewed advanced SSSV technologies, and summarized high strength materials suitable for XHPHT applications. The second stage was the design stage. Since the design of a flapper SSSV is basically an optimization task constrained by very tight spatial limitations, a design-by-analysis was conducted with computer models for XHPHT environments. A comprehensive simulation program was defined for the project including a dynamic stress analysis; 3D transient, multi-phase fluid dynamics with compressible flow; fluid-structure interaction; correlation to classic water hammer; heat transfer; materials science; and control systems. With available software at Rice University, computational fluid dynamics and finite element analysis of temperatures and stress were carried out in ANSYS® CFX v12.0, ANSYS® Workbench v12.0, and SolidWorks *2009*.

**Results:**

- Validated that it would be practical to design a SSSV for operations at a pressure of 30,000 psi while at a temperature of 400°F.
- The study did not specifically address how a new design would be experimentally tested for validation. The valve should be at least tested at the design pressure and temperature. It is difficult to justify an incremental pressure based on a fixed percentage or a fixed value, as current American Petroleum Institute (API) standards suggest. The API should consider setting, or adopting, a standard that defines who is qualified to conduct a proper "analysis" of each and every aspect of the valve design. Usually different experts are required to certify different design aspects. In the relatively mature area of linear and non-linear stress analysis, commercial software tools are often misused by persons without many years of experience.
- The lack of industrial standards for SSSV designs was addressed and possible remedies were suggested based on ASME BPVC Sec. VIII. Although a robust subsurface SSSV is difficult to design considering the time and cost for this graduate project, a prototype of a flapper valve design was achieved through a parametric study and went through the design process. The study showed that stress level at slam shut impact can be reduced within elastic range by a 42% increment of the flapper thickness. Computational Fluid Dynamics (CFD) analysis in the project showed that pressure self-equalizing mechanisms can significantly help reopen a flapper valve after slam-shut by reducing 40% - 80% pressure difference.
- Two high strength structural materials were identified for the design. However, that conclusion is based on a very narrow set of fluid and structural properties. It is critical to vastly increase the range of those data. Cyclic stress-strain curve data for high strength materials will probably be the easiest to obtain or create. XHPHT reservoir fluid/gas properties will probably be the most difficult design data to obtain. Those data seem to be treated as proprietary to reservoir owner. The interests of public safety suggest that such data should be made public.

## Design Investigation of Extreme High Pressure, High Temperature (XHPHT) Subsurface Safety Valves (SSSV)

- Two master degree studies of detailed fluid-structure valve interactions have been made publicly available on the RP-SEA website. One study addressed flapper geometry, while the other dealt with hemi-wedge geometry. All the electronic input and output from those studies has been retained by RPSEA.
- The team faced several difficulties during the project that prevented them from adequately studying the technology. First, critical information on XHPHT fluid properties was not obtained. Second, finding high strength material temperature-related properties, especially cyclic stress strain relations proved to be a challenge during the project and ultimately prevented the team from conducting a thermal analysis. Third, full fluid structure interaction could not be performed in this project due to time constraints and lack of available software.

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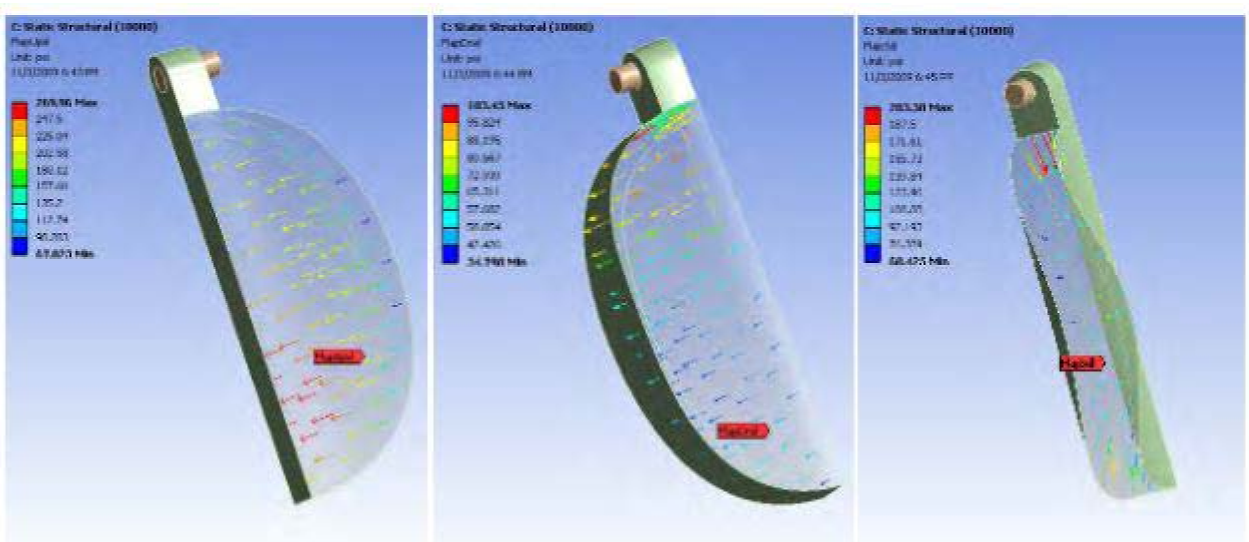
**Project Number:** 07121-1603c

**Period of Performance:** 10/2008-10/2010

Read/download the final report.



(a) Flapupsl (b) FlapDnsl (c) FlapSdl

*CFX pressure mapping on the flapper (35 degree open).*

## Coil Tubing Drilling and Intervention System Using Cost Effective Vessel

**Objective:** To develop a practical, cost-effective downhole intervention system for deepwater satellite subsea wells for enhanced safety of personnel and protection of the environment.

**Research Conducted:** The concept was to use a reusable self-supporting riser (SSR) to extend the well casing up from the seafloor so that existing shallow water interventions systems, including coiled tubing (CT) and wireline, can be used in ultra-deepwater.

The first phase of the project produced the conceptual design of the components needed for the SSR system. During this phase, project researchers through a literature search on offshore use of CT, suitable vessels, and riser modeling and design work addressed challenges faced when using a CT from a cost-effective vessel in deep and ultra-deep water—the size and weight of the CT equipment in relation to vessel deck space and deck load, the effects of water depth and ocean currents on the equipment, and the need to have a riser for circulation. This phase involved research into five major design considerations for the SSR system:

1. Capability of CT to operate in GOM deepwater environment;
2. Design and operation of a SSR that would connect to an existing production tree;
3. Safety designs that would demonstrate that a SSR could operate in the GOM deepwater environment where the well is under constant control, that the CT could be safely cut in the event of a vessel drive-off or some other event requiring a quick departure from the well;
4. Feasibility of using a smaller, non-MODU vessel to install and remove the SSR and to support the intervention activities; and
5. Cost effectiveness for using the SSR intervention activities in the GOM.

A second phase of this technology was conducted under RPSEA project number 10121-4505-01 (p. 33 of this report) and included staging of equipment, mobilization to a vessel, and safe demonstration of downhole work using concepts presented as part of the 2010 and 2011 work.

**Results:**

- The project showed how to safely use cost-effective vessels to install the SSR and perform deepwater intervention work much more efficiently than conventional approaches.
- The hazard identification review concluded that hazards identified during this design phase have been effectively managed and mitigated.
- Project researchers produced a conceptual design of the components needed for the SSR system.
- The challenges regarding the use of CT with a cost-effective vessel in deep and ultra-deepwater were resolved. These challenges include the size and weight of the CT equipment in relation to vessel deck space, the effects of water depth and ocean currents on the equipment, and the need to have a riser for circulation.

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**Project Number:** 08121-1502-01

**Period of Performance:** 10/2009-04/2011

Read/download the final report.

## New Safety Barrier Testing Methods

**Objective:** To determine if an alternative means of conducting safety barrier testing was possible. To achieve this, project researchers focused on providing a more efficient program to monitor performance and leak detection in the ultra-deepwater community related to temperature and pressure differences, and to demonstrate more efficient and effective means of evaluating safety barriers critical to production operations.

**Research Conducted:** Safety barriers—such as production master valves and subsurface safety valves—are vital components for continued oil and gas operations. These safety barriers are particularly important for ultra-deepwater applications for which the failure to hold, operate, and maintain pressure could have catastrophic impacts to worker safety, the environment, and the economics of well operators. Testing of safety valves after installation is a critical task for ensuring safe offshore oil production. These valves cannot be directly tested using conventional measurement methodologies. Instead, pressure monitoring is used. This approach is costly and can result in extended shutdown periods, loss of production, as well as an increased likelihood of flow assurance events.

In the early phases of the project, researchers identified and subsequently ranked a number of safety barrier technologies. Due to the large number of existing wells with the need for this testing, it was decided to avoid technologies that required retrofitting of existing infrastructure, particularly for surface-controlled subsurface safety valves (SCSSVs). A resulting tradeoff study selected well-specific modeling as the most viable technology. A number of analytical and Computational Fluid Dynamics (CFD) models were utilized to study the problem.

The testing of safety barriers in deepwater environments remains a challenge, but this project provided several tools that can be used to augment existing practices in the field. The numerical model developed under this project can be used by operators to interpret pressure buildup testing data. Additionally, even capturing the observations from the models will allow operators to determine the parameters of importance when conducting such testing. This model will help operators determine the operational envelope of their testing. Additionally, the study gives an evaluation of other technologies that might aid operators of specific wells and if additional technologies should be employed.

**Results:**

- A numerical model was developed by project researchers to allow for determination of leakage rates, as well as the required test duration. The model is computationally-inexpensive and allows for the operator to conduct simple trending of results. The sensitivity of various criteria was also explored. The model can reduce overall test times and give operators a sense of the level of uncertainty in interpreting measured pressure changes. Overall, this project demonstrated that such a model can improve the existing approaches to testing of safety barriers. Example improvements could be extension of the calculations to non-idea gas behavior and accommodation of thermal effects such as convection. The results of the model also highlighted the relative importance of such parameters as temperature distribution and level measurement for the liquid column. Invoking technologies, such as distributed temperature sensing, that could reduce overall uncertainty would benefit from the use of such models.
- A comprehensive set of CFD models was evaluated to determine the behavior of a pseudo-static column during the leak test of a safety valve and help advance previous modeling efforts focused on this problem. The CFD work has highlighted some areas of computational weakness when studying such a complex physical system. The application of a more-straightforward analytical model provides improved uncertainty when evaluating pressure measurements from the field.
- A significant finding of this work is that thermal effects of the well must be accounted for in order to properly interpret pressure results. During testing of a safety valve, in which the column had stratified and there was a gas cap at the top, the gas pressure (1) decreased as the gas cooled, (2) decreased as the liquid column cools and shrinks, expanding the gas, and (3) increased as leaked product enters the column. The interaction of these three components is complex, but straightforward modeling can be used to generate trending curves for evaluation of the valve integrity. Normalizing some of the parameters allowed for the same model to be used on the same well family over the course of its life with little modification. Since the thermal behavior of the column significantly impacts the results, further studying the temperature of the fluid would assist in evolving the technology.

## New Safety Barrier Testing Methods

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**Project Number:** 08121-2101-02

**Period of Performance:** 01/2010-04/2012

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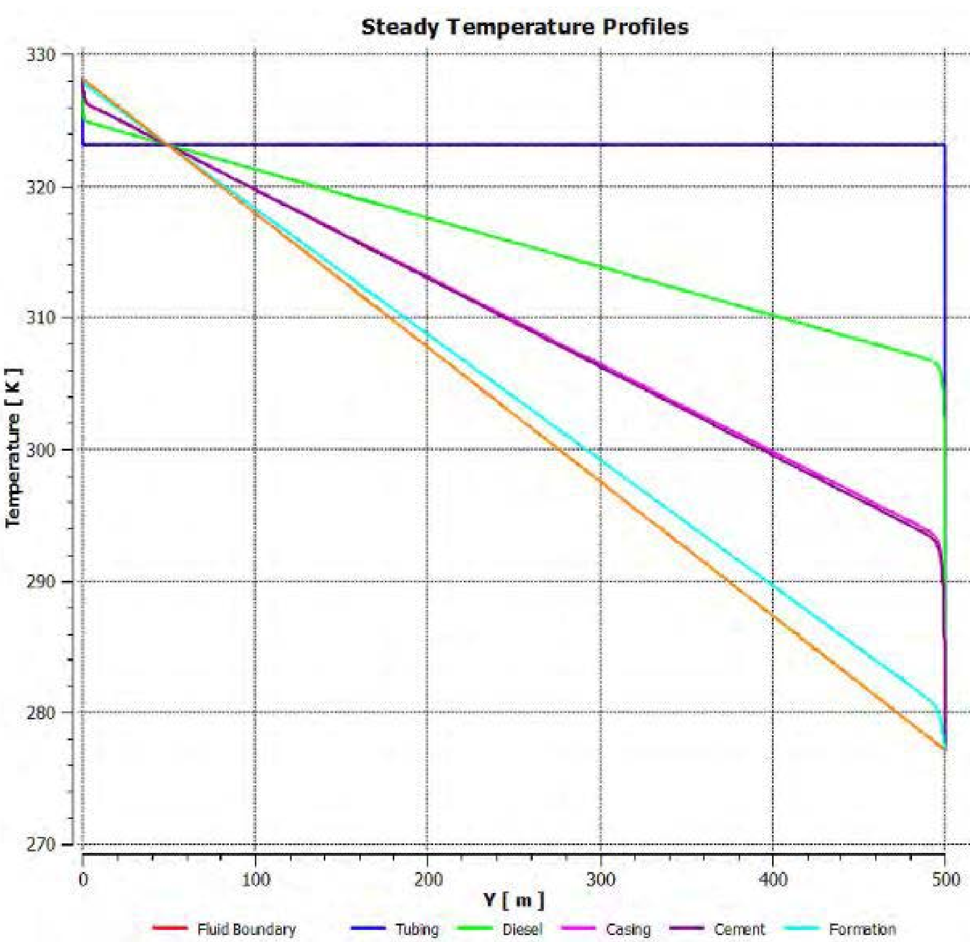


*Steady Well and Formation Temperature for Flowing Well. The CFD predictions for the fluid temperature were used as an initial condition for the analytical model. The SCSSV is located at a value of 0 on the x-axis.*

## Early Reservoir Appraisal Utilizing a Well Testing System

**Objective:** To define appropriate cost-effective systems for testing deepwater reservoirs during the appraisal stage to enhance safety for personnel and the environment, and to avoid the use of expensive production and storage equipment.

**Research Conducted:** Well testing in the early reservoir appraisal stage helps industry gather useful information that they can use to decide the economic potential of field discoveries and safely commercialize them. Deepwater well testing in the Gulf of Mexico (GOM) has not been economically viable or practical, primarily due to the high cost of conventional equipment and environmental and safety risks. Without knowing the size and production potential of a discovery, the consequences is that hundreds of millions of barrels of potential commercial reserves discovered in the GOM and in other deepwater regions of the world will not be produced because the risks are too high.

A team of subject matter experts, whose experience covers many technical disciplines, was assembled to address issues involved with deepwater well testing for early reservoir appraisal. The project started with extensive analyses and well test simulations of three major reservoir geological plays (Middle Miocene, Lower Tertiary Paleocene, and Lower Tertiary Eocene) in the GOM to determine reservoir and fluid characteristics.

### Results:

- The reservoir modeling led to design of eight well testing systems that can be used for short-term, long-term, interference, and injection testing. Each system was analyzed for operational feasibility in reference to subsea and surface safety systems, and vessel requirements, with the focus of reducing risks to personnel, the environment, equipment, and complying with all applicable regulations.
- The reservoir analysis conducted during the project provided industry with guidance as to which well test method would offer the best results in terms of the type of well test to perform, what the duration and flow rate would be, and estimations on expected outcomes to better characterize the reservoir.
- The well test system architectural designs and operational feasibility analysis gave industry all the available options for deepwater well testing in regards to downhole, subsea, surface, and vessel requirements, with an extensive focus on safety requirements. Providing this information to industry professionals and operators will improve their ability to more accurately make decisions about production capacity and commerciality of a field/reservoir.
- The injection test simulation results were very encouraging. The final data correlates to results of conventional production tests and the injection tests require less time compared to the duration of conventional tests. One of the most important advantages of the injection test is there is no live oil produced to the surface. This reduces environmental concerns regarding the flaring of gas at the surface and eliminates the need to store or off-load produced oil. The findings of the injection test warrant further investigation, beyond the scope of this study, to ensure that these test can be used a viable alternative to conventional well tests.
- Project results were used to design template for a web-based computer modeling tool that once fully developed will provide operators greater decision making capabilities on which well test design to use.
- During project well testing, substantially reduced flow rates produced the same results as maximum flow rates. These lower flow rates resulted in less produced fluids (oil, water, and gas) returning to the surface, thus reducing storage and disposal requirements.
- Numerous well test simulations showed that production rates between 1,000 BOPD to 2,000 BOPD would give the necessary pressure versus time results to do classical pressure transient analysis. This discovery indicates smaller facilities and storage are required and deepwater testing can be done less expensively, and in less time.
- A representative set of injection well test simulations yielded the same end results as production and build-up tests. This could lead to an eventual field test on a GOM well.
- All eight systems designed and developed during the project were found to be viable and feasible.

## Early Reservoir Appraisal Utilizing a Well Testing System

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**Project Number:** 08121-2501-02

**Period of Performance:** 10/2009-03/2011

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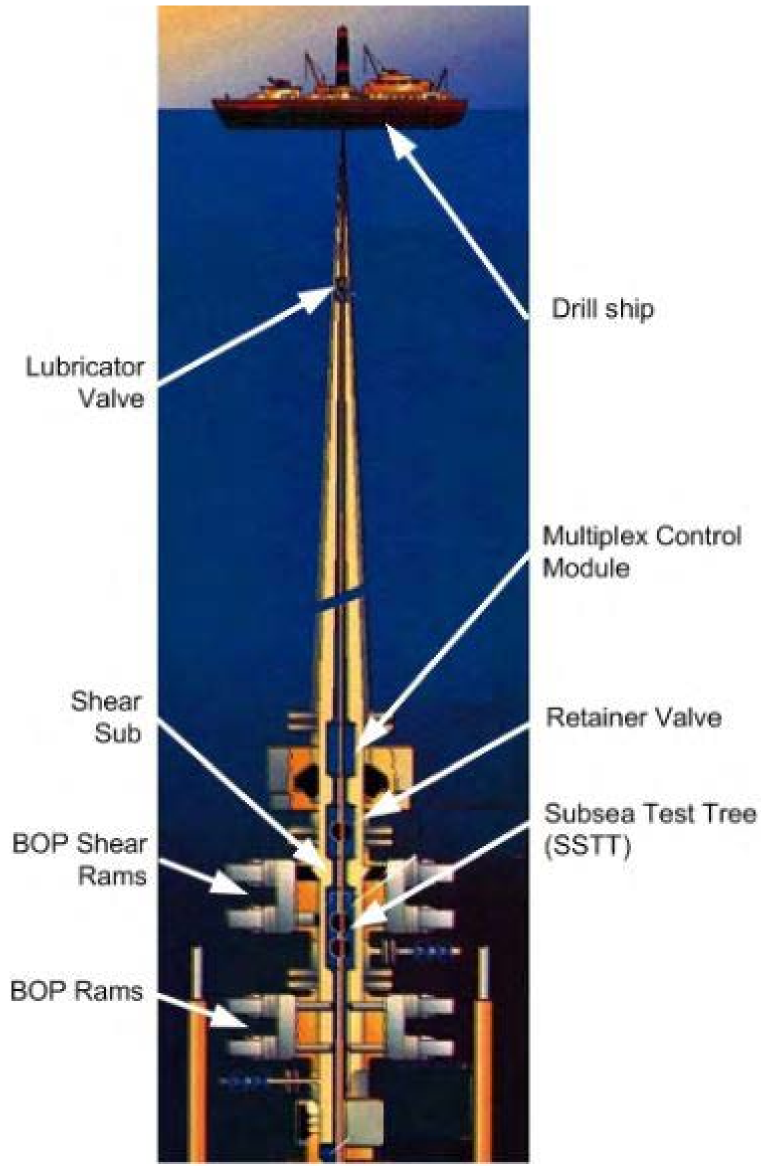



*Example of Deepwater Landing String.*

## Advanced Steady-State and Transient, Three-Dimensional, Single and Multiphase, Non-Newtonian Simulation System for Managed Pressure Drilling

**Objective:** To bring state-of-the art models that exceed commercial capabilities and their newer counterparts to Managed Pressure Drilling planning to provide an integrated software platform for the entire circulation system that will set new industry standards.

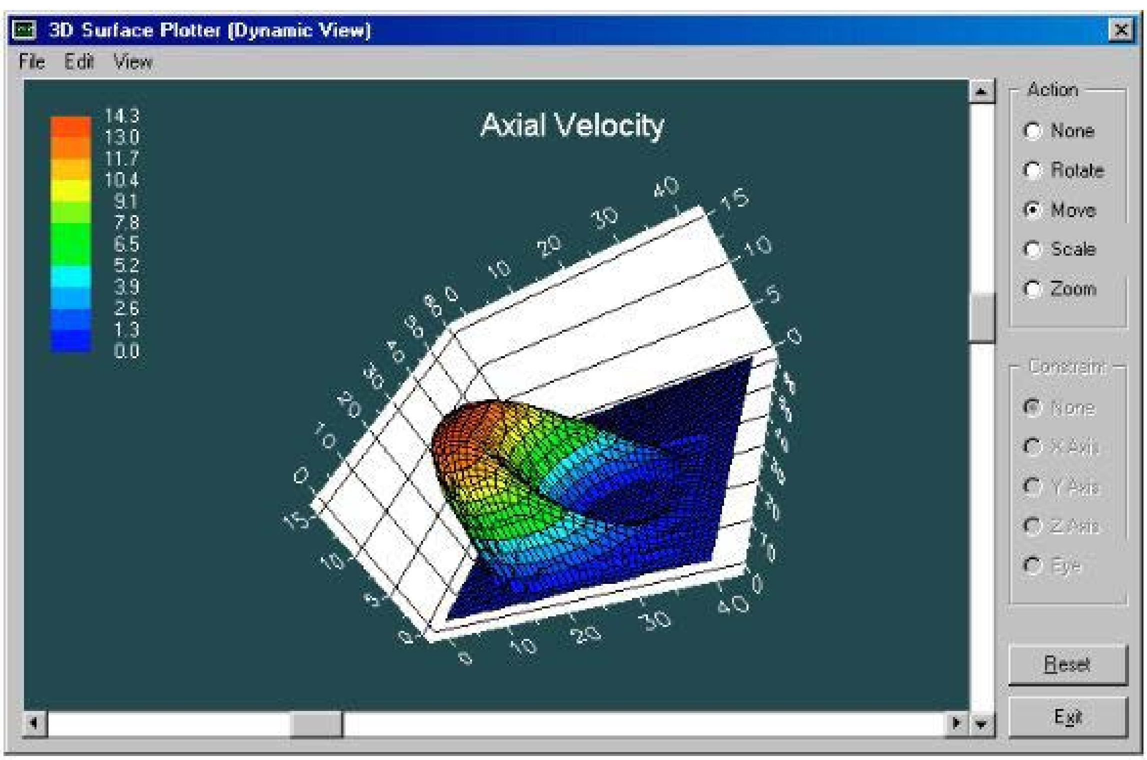
**Research Conducted:** Managed pressure drilling focuses on closed-loop feedback and control systems vital to safely and efficiently drilling ultra-deepwater wells, where narrow pressure windows dictate the difference between success and failure.

Accurate flow modeling has been lacking in the highly eccentric borehole annular cross-sections typical of modern deviated and horizontal wells, necessary for job planning and rig site, use in both drilling and cementing, and for precise real-time machine control.

This study focused on developing fully predictive accurate pressure profiling methods along general well paths by solving rigorous mathematical models that do not bear the limitations of ad hoc assumptions implicit in mean hydraulic radius, slot flow, multiphase empirical correlation and like approaches.

**Results:**

- Highly eccentric borehole annuli (with possible washouts, cuttings beds, and fractures) were described using custom boundary-conforming curvilinear grids, and the general steady and transient, non-Newtonian flow equations were written to and solved in these special coordinates.
- The numerical methods used, fast and extremely stable, were hosted by user-friendly, "plain English," graphical interfaces (with integrated 3D color capabilities) that support job planning efforts and particularly on-site field use. The team's guiding development principle was clear and simple: scientific rigor usable "out of the box" with minimal training and engineering expertise.
- The general problem, considered in multiple physical limits, was cross-validated through close agreement with different models solved by contrasting methods in regimes of common overlap, and field data and laboratory experiments where possible.




*"Dynamic 3D" display with mouse-rotatable perspective views.*

## Advanced Steady-State and Transient, Three-Dimensional, Single and Multiphase, Non-Newtonian Simulation System for Managed Pressure Drilling

- The overall work—while providing powerful new advances in modeling detailed pressure and stress fields—generalized borehole flows and developed many "firsts" which have immediate practical application.
- Plug zone size, shape, and location were rigorously calculated for general yield stress fluids on arbitrary annular cross-sections.
- Detailed hole geometry and rheology were accounted for in swab-surge analysis.
- Hole cleaning correlations are now possible based on quantitative assessments on yield stress, pipe rotation and reciprocation, and geometry.
- Use of drillstring rotation as a simple and effective means for pressure control was demonstrated computationally with pressure-while-drilling log data.
- Extremely fast and stable real-time methods for "cement displacing mud" applications were developed to be conveniently run at the rig site.
- The research and development was well received by the industry and became the subject of four papers presented at the 2011 American Association of Drilling Engineers (AADE) Conference and one at the 2011 Offshore Technology Conference (OTC).
- Elsevier Scientific Publishing published the research, plus practical applications, as a new book that was debuted during 2012 at OTC.

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**Project Number:** 08121-2502-01

**Period of Performance:** 10/2009-04/2011

Read/download the final report.

## Fiber Containing Sweep Fluids for Ultra Deepwater Drilling Applications

**Objective:** To improve the understanding of (drilling fluid) fiber sweeps through experimental and theoretical studies in an effort to develop fiber sweep systems, improve hole cleaning in UDW drilling operations, minimize hole cleaning related problems, create models to predict fiber sweep performance and optimization, and recommend fiber sweep best practices. The knowledge gained through this project will help oil and gas operators reduce their drilling costs, improve operational safety, and develop sweep technology that minimizes the impacts of drilling on the natural environment.

**Research Conducted:** Project researchers first performed a review of fiber sweep literature and then carried out theoretical studies to better understand the performance of fiber sweeps. The stability of fiber sweep was theoretically and experimentally investigated to develop a model that could predict the separation of fiber during the application fiber sweep. In addition, settling behavior of particles in fiber sweeps was studied in the effort to minimize the deposition and accumulation of rock cuttings in the wellbore.

Sedimentation experiments were performed using the base fluid and fiber sweeps to determine the contribution of fiber drag (i.e., drag force that originates due to hydrodynamic and mechanical interactions of fibers and solids particles) to the total drag force. Applying a fiber drag correlation developed using the sedimentation experiments resulted in a formulating a mechanistic cuttings transport model to optimize the fiber sweep performance in the field. Hole cleaning efficiency was investigated varying inclination angle, fiber concentrations and pipe rotation speed. The results of the hole cleaning experiments were used to validate the mechanistic model.

**Results:**

- Tests conducted with varying fiber content from 0.00 to 0.08 percent indicated the absence of excessive thickening, which is frequently observed in highly concentrated fiber suspensions and that fiber sweeps are not vulnerable to excessive thickening.
- When researchers added fiber into a drilling fluid it substantially reduced the settling velocity of cuttings and improved fluid carrying capacity. The velocity reduction came from the improvement of the drag force that opposes the motion of the particle. After obtaining settling velocity measurements, the investigators determined the contribution of the fiber drag to the total drag force. The fiber drag is strongly related to viscous properties of the fluid. The predictions of the cuttings transport model, developed during the investigation, showed good agreement with experimental results at low and intermediate flow rates.
- Fiber sweep and flow loop experiments showed that fiber sweeps substantially improved cuttings removal compared to base fluid sweeps, despite similar equivalent circulating densities. The flow loop experiments showed that adding fiber to sweep fluid had a significant effect on the hole cleaning efficiency when applied in conjunction with inner pipe rotation.
- Neither oil-based nor synthetic-based fluids exhibited any significant shear viscosity sensitivity to fiber concentration at ambient temperature. Structured fluids such as oil-based and synthetic-based fluids were shown to create more stable fiber suspensions. It may be possible for oil-based or synthetic-based mud sweeps to be utilized in the field.

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**Project Number:** 08121-2902-07

**Period of Performance:** 01/2010-01/2012

Read/download the final report.

# Intelligent Production System for Ultra Deepwater with Short Hop Wireless Power and Wireless Data Transfer for Lateral Production Control and Optimization

**Objective:** To develop a safe system that would optimize production in multilateral wells and increase the life of the wells while decreasing costs. The system was to provide remote flow control capabilities inside the laterals using an electric, ultra-low power choke system with production data collection capability in real time. It could wirelessly transfer data and power from the main bore to the laterals. Power transfer was also to be accomplished from an upper to a lower completion over long distances, so that gauges and flow control modules can be deployed closer to the producing zones along a wellbore.

**Research Conducted:** Tubel LLC utilized its experience in developing downhole tools and sensors to create a unique system for remote control and production and reservoir monitoring. The University of Houston partnered on the project to develop a game changing downhole wireless power transfer system that complements the control and sensing system. The original concept was to design a remotely operated downhole flow control module that could be placed in wellbore laterals for real time reservoir to wellbore flow control. Production sensor requirements were finalized once the flow control original concept was validated in a lab. Theoretical work performed by the University of Houston was proven to provide power from the main bore into laterals without the need of a cable.

**Results:**

- A highly efficient engineering module capable of operation with a small battery pack was developed. Sensor technology that allows for a pressure, temperature, flow meter and fluid identification package to be placed in the laterals for real time data gathering was created and lab tested. A working prototype of the low power flow control and data acquisition transmission system was developed and tested in a lab setting. The system was modified for field use and was then tested in a flow loop. Finally, it was ruggedized and tested in the field.
- The system provides a new way to control and monitor production by integrating sensors into a flow control device and having a system operating at ultra-low power in which the opening and closing of the flow control requires 1.2 Watts of power, compared to industry standard 50 Watts of power required for inner sleeve-based electric flow control systems. The new system also has four flow control ports that provide production control flexibility by being able to choke the flow with minimum erosion. The flow control provides a larger inside diameter and smaller outside diameter than normal, allowing for higher flow rates through the tool, as well as system installation in smaller diameter casing, which may save the operator a significant amount of money.
- There were quite a few issues that had to be addressed during the project. Sliders had to be coated to reduce friction, which reduced the power required to open and close the tool. A ring that holds a mechanical sleeve for permanently closing the tool was redesigned to allow the ring to expand once it reached a proper location. Shaft length for a motor driver interface had to be increased to permit sliders to travel the length of the opening in the tool. A power module had to be modified to provide protection for input and to prevent high voltage damage. Motor drivers were also modified to protect the driver circuit from failure due to fly back current, which occurs when the motors are turned off. A tank circuit was also added to the driver circuit to absorb the fly back current. The surface system had to be modified once test results indicated that timing was not correct during transmission of data that was recorded in tool memory after the motors were actuated. A local LCD display and keyboard were added to the surface system to allow the system to send commands in the well without a personal computer being attached to the surface system.

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**Lead Performer:** Tubel LLC

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**Project Number:** 09121-3500-01

**Period of Performance:** 01/2011-03/2013

Read/download the final report.

## Fatigue Testing of Shrink-fit Riser Connection for High Pressure Ultra-Deepwater Risers

**Objective:** To make "project ready," connection of steel riser components, using a thermal Shrink-Fit assembly method. This Shrink-Fit connection is a technology that facilitates the fabrication of riser joints from high and ultra-high strength steel [80 - 130 kilo pounds per square inch (ksi)], for which welding may not be preferred. The project involved hydrostatic and resonant fatigue testing of a Shrink-Fit connection to enable the avoidance of welding, and fabricate riser joints from high and ultra-high strength steel.

**Research Conducted:** Fabricating critical risers for use in ultra-deepwater high-pressure wells is a major challenge for the offshore industry. Industry must use high wall-thickness or high-strength steel for risers in these environments. These types of steel are problematic because they are difficult to weld.

Researchers used six large scale specimens in the project in place of full bore (21 inch) high pressure shrink-fit couplings to demonstrate that pressure containment is maintained for maximum working and hydro-test pressures and to target fatigue life is achievable without loss of pressure integrity in the connection. The couplings were fabricated from American Society for Testing and Materials (ASTM) A182 Grade F22 [7] modified, 80 ksi forging stock. The 11.75 inch OD, 1.1 inch WT SM-C110 [6] pipe was supplied to the project by BP and machined by Subsea Riser Products (SRP). After machining, the two pipes were connected together using a shrink-fit coupling. This occurred as and when pipe and couplings became available.

For the shrink-fit assembly process, researchers expanded the female coupling or flange through application of heat, and carefully inserted the pipe. The heat was provided by portable induction heating equipment. Since the connection is a coupling, the assembly was carried out in two steps. First the pipe was lowered into the coupling which rests on an alignment plate on the ground, and after it cooled, the entire connection was up-ended into an assembly tower. The second shrink-fit operation was performed and the entire sample was lowered down to cool. When assembly was complete, project engineers welded end-cap plates inside the ends of the pipe for pressure containment. A large fillet weld was laid down, which was then stress relieved by post weld heat treatment. The resulting assemblies were pressure tested at the designated test pressure of 22,500 pounds per square inch gauge (psig). Fatigue testing commenced as soon as fatigue bay, test specimen and availability allowed. The procedure was driven by a qualification test plan with specimens comprising 12 shrink-fit connections tested over a period of approximately one month.

**Results:**

- Through qualifying such a system that can be manufactured from steel in excess of 80 ksi, the wall thickness of the pipe can be significantly reduced, which in turn will reduce the weight, current loading (due to reduced diameter), tensioner requirements, and cost of manufacture of critical deepwater riser systems.
- Manufacturability of a SRP Shrink-Fit connection was proven during the project with no issues and without selective assembly. 100% of the coupling samples (12/12 connections across 6 samples) passed the hydrotest pass rate at 22,500 psig (15 ksi working pressure) with no sealing issues.
- The fatigue life of the connection has been proven comparable to a 'best in class' DNV-RP-C203, C1 welded couplings with a stress concentration factor of 1.46. This is better fatigue resistance than is normally considered for welded connections of this type used on deepwater drilling risers (typically E-Class 1.3).
- Failure occurred in all cases by slow leaks out of one side of the coupling, the cause of failure was cracking of the pipe where it enters the flange. It was evident that secondary locking was not engaged and this was evidence that the hydrotest did not overcome friction fit of the connection, nor did the repeated action of the resonant fatigue test, combined with the tension due to end-cap load, case the coupling to 'walk' along the pipe and engage the secondary locking.

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**Lead Performer:** Subsea Riser Products

Simon Luffrum, Subsea Riser Products

**Project Number:** 09121-3500-02

**Period of Performance:** 04/2011-09/2012

Read/download the final report.

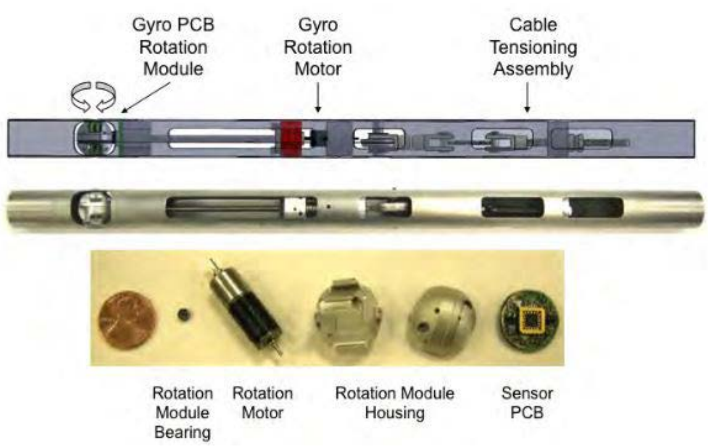
## Gyroscope Guidance Sensor for Ultra-Deepwater Applications

**Objective:** To improve ultra-deepwater drilling by developing an inertial guidance system that can handle high temperatures, is vibration resistant, and is based on micro-electro-mechanical systems (MEMS) gyroscope technology.

**Research Conducted:** There were three main components of the research: (1) design of a high-temperature circuit design, (2) optimization of MEMS sensing elements, and (3) assembly and test of the system. The approach was to design and fabricate the mechanical sensing structure separately from readout circuits and then to integrate them together as a hybrid assembly using the team's low-loss microbump process. Control electronics were upgraded with new circuit components that are smaller and can handle the higher temperatures that would be seen in a down-hole drilling environment. Thickness of the sensing element was increased to make the MEMS sensing structure more robust. Electrostatic combs were also increased to improve sensitivity. Increasing the thickness of the device makes the silicon etching process more challenging. To meet this need, process development and qualification runs were completed to ensure the gyroscope could be manufactured to design specifications.

**Results:**

- The team successfully fabricated an inertial guidance system for ultra-deepwater drilling, which included an integrated MEMS gyroscope mechanical sensor and robust readout circuits that can operate in ultra-deepwater environments, i.e., high temperatures and high vibrations/shock.




*Design and components of the Gyroscope module.*

- The sensor was successfully operated by the team without failure at 140°C inside a vacuum test chamber. The team developed an electronics circuit to accompany and verified that it functions at elevated temperatures of 200°C inside an oven.
- Use of these gyroscopes enables the system to be positioned next to drill bits, a significant improvement over conventional systems that must be installed 50 to 80 feet behind a drill bit. The shortened reaction could potentially enable a greater volume of the reservoir to be accessed from a single surface location, decreasing drilling costs and environmental impact, and accelerating exploration into emerging plays.
- When processing the MEMS sensing element, some malfunctions and process modifications occurred. Notably, a surface technology systems (STS) deep reactive ion etcher (DRIE) tool was damaged in a power outage. This required replacement of a turbo vacuum pump, as well as computer malfunctions, which were repaired.

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**Lead Performer:** Laserlith Corporation

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**Project Number:** 09121-3500-10

**Period of Performance:** 01/2011-09/2013

Read/download the final report.

## Smart Cementing Materials and Drilling Muds for Real Time Monitoring of Deepwater Wellbore Enhancement

**Objective:** To develop drilling muds and cement slurries with properties that can be monitored in real time (smart drilling mud and smart cement slurry) to improve and verify wellbore integrity. Specific objectives for Phase I were 1) to use changes in the electrical resistivity properties of cement and drilling mud in developing smart cement slurry (SCS) and smart drilling mud (SDM) with enhanced sensing capabilities for real-time monitoring during installation and service life of the well, and 2) to control fluid loss by modifying the drilling mud and cement slurry without affecting the sensing properties.

**Research Conducted:** Exploration and production of oil and gas from deep water environments present unique challenges in well construction. In particular, it is critical to monitor, in real time, the advancement of the fluid fronts (drilling mud and cement slurry) to better control the fluid losses in various rock formations and to minimize the loss of fluids to optimize the cementing operation. At present there is no direct real-time observation method available to determine the location of the advancing cement slurry front in the borehole. Also there is no reliable method to determine the length of the competent cement supporting the casing and no real-time monitoring of the cemented casing performance over the service life of the well.

Researchers performed a series of experiments to evaluate the behavior of oil well cements and drilling mud with and without modifications.

Electrical resistivity was selected as the sensing property for both cements and drilling muds; two parameters (resistivity and change in resistivity) will be used to quantify the sensing properties. A conductivity probe, digital resistivity meter, and four and two probe method were used to measure resistivity. Standard viscometers were used to quantify the viscous properties (yield point, plastic viscosity) of various cement and drilling mud mixes. The Vicat setting test (ASTM C191) was used to determine the initial and final setting times for hydrating cement mixtures. A commercially available extensiometer (accuracy of 0.001% strain) was used to measure strain. High pressure/High temperature (HPHT) device was used to study the effect of fluid loss in the cement.

*Cements*: In this study commercially available Class G and Class H oil well cements were used. Cement tests were performed from the time of mixing to hardened state behavior. Varying amounts of carbon fiber (0.075% to 0.2%) were added with the cement mix as base modification; various other additives (silica fume, fly ash, bentonite, nanoparticles, meta-kaolin and water reducing agents) were added during the experiments depending on the desired result. Cement was placed in cylindrical mold. Four wires were placed in the mold with two wires on each side of the specimen. During the initial stages of setting, conductivity and API resistivity meters were used to determine the curing cement resistivity. The specimens were subjected to compression tests (ASTM C39) to measure strain. The change in resistance was monitored and was used relate the changes in resistivity to the applied stress. Fluid loss amount and rate were measured at intervals in the cement slurry and compared at different applied pressures.

*Drilling Muds*: Wyoming bentonite was added to water-based drilling mud. Oil based muds were prepared with both mineral oil and vegetable oil and 4% bentonite. Varying amount of oil was used to test sensing properties. Ester-based synthetic muds were also used to study behavior. Various other additives including surfactants, carbon fibers and fluid loss reducing agents (salts, gum), starch and barite were used in this study.

**Results:**

- *Cement*: Class H and Class G oil well cements were used to demonstrate the potential of making the material, from the time of mixing to solidified state, more piezoresistive and sensing without significantly affecting the rheological properties. Unmodified cement was used as the baseline for comparison. Cement curing can be characterized by several resistivity parameters. Changing the water-to-cement ratio from 0.38 to 0.44 increased the resistivity by 30% and reduced the time to reach the minimum resistivity by 30 minutes. During the curing of the cement, initial resistivity reduced by about 10% to reach a minimum resistance and maximum change in resistance within the first 24 hours of curing varied from 50 to 300%. The addition of 0.1 % carbon fiber to the cement reduced the initial resistivity and made the material piezoresistive; the resistivity change due to applied stresses was 30 to 80 times higher than the change in the strain in the material, making the cement material smart and sensing. Also the addition of 0.1% carbon fiber did not affect the rheological properties of the cement. For the carbon fiber modified smart cement, the resistivity

## Smart Cementing Materials and Drilling Muds for Real Time Monitoring of Deepwater Wellbore Enhancement

change at peak stress was about 400 times higher than the change in the strain. Hence carbon fiber modified cement will be used Phase II. The addition of 0.1% of carbon fiber made the cement with other additives such as nanoparticle and silica fume more piezoresistive. Contamination of the cement by bentonite can be detected based on the change in resistivity. Bentonite reduced the fluid loss in cement.

- *Drilling fluids*: Water-based muds: An increase in bentonite from 2% to 6% reduced resistivity by 40%. Salt contamination also causes a reduction of resistivity; an addition of 0.1% salt reduced the resistivity by 40%. The addition of xanthan gum and corn starch were found to control the fluid loss. The resistivity of water-based drilling mud with 6% bentonite is over 400% higher than the initial resistivity of cement slurry; the difference will help in the monitoring the displacement of drilling mud and cement injection during the installation of the casing.
- *Oil-based muds*: Reducing the oil-to-water ratio from 4:1 mix to 1:1 mix reduced resistivity 100 times. Resistivity can also be substantially reduced by adding surfactant.
- *Synthetic-based muds*: Resistivity can be increased by increasing ester-to water ratio. Carbon fibers caused and decrease in resistivity; the increase from 0.1 to 0.2% carbon fibers reduced resistivity by 10%.
- Resistivity can be used to evaluate and track the performance of cement and drilling muds. Changes, such as composition, curing, stress, cracking, fluid loss and temperature, can be correlated to resistivity and change in resistivity to support the monitoring of cement and drilling mud/fluid behavior.
- Tracking resistivity and changes in resistivity in drilling muds and cement provides a real-time solution in tracking the location of the advancing cement slurry front in the borehole, and a method of determining and monitoring the length of the competent cement supporting the casing.

  Using electrical resistivity for monitoring both drilling muds and cement can be performed with the same instruments in real time.

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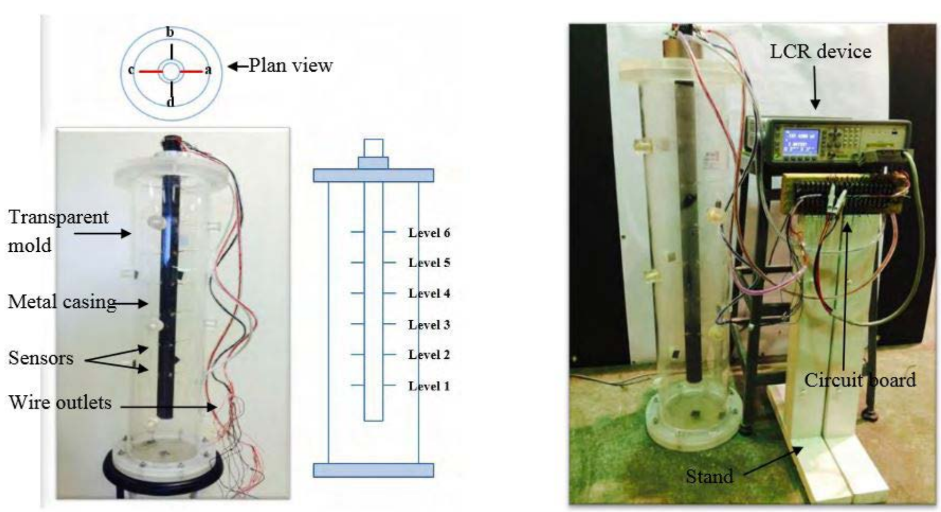
**Project Number:** 10121-4501-01

**Period of Performance:** 08/2012-08/2016

Read/download Phase 1 final report and Phase 2 final report.




*Laboratory scale oil well model and monitoring system.*

## Deepwater Reverse-Circulation Primary Cementing

**Objective:** To assess the viability of performing Reverse-Circulation Primary Cementing (RCPC) to reduce circulation pressure requirements for deepwater wells, determine required technology to apply RCPC for deepwater wells, and present development strategies for required technologies.

**Research Conducted:** In RCPC fluids are pumped downhole via the annulus and then up into the casing, in contrast to a conventional cement job where fluids are pumped down the casing then up into the annulus. The RCPC process reduces friction pressures and equivalent circulating densities (ECD) because it does not require fluid to be lifted all the way up the annulus as during conventional cementing.

The application of RCPC to deepwater wells is expected to reduce bottomhole circulating pressures and prevent lost circulation during cementing as well as increase safety, enhance environmental sustainability, provide zonal isolation, and improve cement seals. Other benefits that have been seen through the application of RCPC include reduced placement time, reduced excess pumped and a reduction in the amount of retarding additives used in the cement. In some cases, RCPC can significantly shorten operational time for cement placement. Simulations and determination of the critical depth can determine if RCPC is viable for that string since in RCPC can result in an ECD reduction during placement. Weak formation or zone needs to be below the critical depth for RCPC to have an advantage

This project was conducted in two phases. Phase I objectives were to confirm, evaluate and address expected challenges and benefits of RCPC in deepwater drilling. Phase II of the Deepwater RCPC project focused on a more detailed analysis of deepwater RCPC technical requirements and the development of finite-element simulations.

Phase I focused on researching the technologies currently available for reverse-circulation primary cementing, and documenting technological innovations that need to occur for the process to be used in deepwater applications. Petroleum industry operating and service companies, and experts with deepwater and reverse circulation experience were involved in information collection. Another area of research involved the development of a series of simulations and numerical models applicable to RCPC operations in deepwater including finite element modeling, temperature simulations, and cement placement. Modeling and simulations used a well schematic where fluids are pumped down the drill pipe below the blow-out preventer (BOP) stack and then diverted into the annulus near the liner or casing hanger through a crossover tool.

Mechanical components required to implement RCPC in deepwater wells were also investigated and analyzed. This evaluation was performed by Weatherford, and included analysis of cement flow and placement controls required to direct fluid down an annulus of a deepwater well casing or liner, and a means to separate fluids during placement. Cementing material considerations were also studied to identify potential design and performance benefits and issues based on cement performance under deepwater conditions when placed by RCPC. Considerations included fluid intermixing, key aspects of spacer design, additive sensitivity, and wait-on-cement (WOC) time. This analysis and evaluation was conducted by CSI Technologies.

Operational performance of RCPC in deepwater was another key aspect investigated in Phase I. Anticipated issues included liquid additive proportioning for accurate cement formulation, mixing rates and cement deliverability, measurement of displacement volumes and measurement of downhole and return flow rates.

Phase II built on the results of Phase I and focused on a more detailed analysis of deepwater RCPC technical requirements and the development of the COMSOL simulations. Preliminary models were refined and developed in more detail, with a focus on ECD and pressures during placement. Specific crossover tool requirements were identified for development and compatibility, and methods to control fill-up and flow back and minimizing flow restrictions during placement were identified for further study. In evaluating cement optimization and spacer design, variations in circulation temperature, thickening time, compressive strength development, gel strength development, stability and fluid loss, design and use of viscous pills for downhole fluid separation as an alternative to mechanical separation were investigated. Researchers also prepared an operational plan to successfully implement RCPC in deepwater and a contingency plan for all major expected contingency situations.

## Deepwater Reverse-Circulation Primary Cementing

### Results:

- *Phase I*: Phase I research on current RCPC technologies identified several challenges. In order to prevent incomplete cementation around the shoe or implacing a large amount of cement that will need to drilled through, a method of determining when cement reaches the shoe is required. Specialized float equipment needs to be available to circulate fluids and perform RCPC operations; conventional float equipment cannot be used. Large variations in temperatures from the surface to the bottom of the hole in deepwater environments requires modifications in cement design. And lastly, computer simulations are inadequate to model parameters such as ECD, pump rates, friction pressures, temperature gradient and mud removal efficiency for cement designs and emplacement. Specifically, Phase I identified the following development areas:
    - Mechanical placement controls: A switchable crossover with 3 positions that can switch back and forth from 1) conventional flow direction to 2) direct flow to annulus side of casing and 3) back to conventional flow.
    - Standard commercially available software packages are unable to model the flow path of deepwater RCPC. A COMSOL Multiphysics finite-element software package has been used to develop a model capable of handling the reverse-circulation cementing process; after simulations applicability to deepater RCPC operations will be evaluated.
    - After investigating cement rheological and density hierarchy effects, researchers identified a need for more information on the effects of well geometry, eccentricity and deviation, and the quantification of these effects in order to provide best practices for RCPC fluid design.
- *Phase II*: Phase II investigations concluded that the applicability and benefits of RCPC to deepwater wells should be evaluated on an individual basis.
    - Development of a mechanical switchable crossover that can be placed in various locations in the well; float equipment placement should be determined on each individual well; and various methods, such as balls, darts, radio frequency identification (RFID) tags, chemical tags, mud pressure pulse, wire drill pipe, hydraulic control lines from the surface, mechanical or gas powered springs, or any combination, could be used to detect the location of fluids downhole or trigger the operation of downhole crossover tools or valves.
    - A method was developed to be able to use workarounds within commercial cementing simulation software to perform deepwater RCPC simulations. The resulting temperature and pressure profiles are somewhat simplistic. A new model was built on the COMSOL Multiphysics software package, which predicts temperatures and pressures/ECDs during a RCPC job. The model was applied to several example cementing jobs; results indicate that overall the bottom-hole circulating temperature is increased significantly in reverse cementing. ECDs at bottom-hole conditions are reduced significantly, and ECDs at the previous shoe can either increase or decrease depending on the configuration of the well. The fact that ECDs can be increased at the previous shoe is a significant issue. If the ECD is reduced at bottom-hole and increased at the previous shoe, then there is a point between those two where the pressures in conventional and reverse circulation are equal. The location of this point with respect to a weak zone or zone of interest in the annulus will be a factor in determining if RCPC is advantageous in that particular application.

*Interface between viscous pill (white) and brine (red).*

## Deepwater Reverse-Circulation Primary Cementing

- Slurry considerations for RCPC are expected to be similar to conventional deepwater primary cementing slurry considerations. Slurry systems can be tailored to optimize compressive strength development. Alternative density hierarchies are possible with RCPC placement. Rheology is a key parameter in fluid design and placement.
- Equipment type and configuration can be selected based on operator and regulatory needs, and what is most appropriate for the expected well conditions. Preparing personnel on location for the reverse operation will be specific to the type of equipment that is used and/or developed for the operation. Possible contingency situations need to be reviewed and plans should be covered as part of personnel training/pre-job procedure.
- The applicability and benefits of RCPC to deepwater should be evaluated on a case-by-case basis. Existing gravel pack and sting-in float technology can be modified for use in the near future. However, technology needed for future development includes the modification of float equipment and a switchable crossover that will divert fluids on demand.
- The next step in tool development should add capabilities that allow for nonmechanical operation of tools from the surface by incorporating technologies such as RFID, chemical-activated triggers, or mudpressure pulses.
- Mud removal and fluid separation will remain a major challenge for deepwater RCPC since physical separation will need to be maintained through the use of viscous plugs instead of traditional plugs, darts, or balls. The design methodology of cementing fluids is affected by this change in placement method since the leading edge of cement will become the critical shoe slurry. A close review of simulations of various wells and casing strings reveals that cement slurry is often exposed to a higher downhole circulating temperature, and that placement time can be shortened significantly in some cases. Hydraulic analysis of these deepwater strings has confirmed the critical depths at which placement by RCPC results in a lower ECD.

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**Project Number:** 10121-4502-01

**Period of Performance:** 06/2012-06/2014

Read/download the final report.

## Intelligent Casing-Intelligent Formation Telemetry (ICIFT) System

**Objective:** To identify reliable technologies that might be applied to make the production casing "intelligent", allow safe and effective deployment, and ensure highly reliable and effective data transmission to the surface in real-time.

**Research Conducted:** With the expansion of deepwater drilling and requirements for safe operation, especially during cement integrity evaluations, the need for real-time distributed measurements during casing and early production has become increasingly crucial. This project focused on the development of an "intelligent" formation telemetry system. An Intelligent Casing – Intelligent Formation Telemetry (ICIFT) design places sensors in the formation, in the cement, or in other locations outside the production casing.  The system is required to record data across all points of the producing zone.

Researchers reviewed and assessed existing borehole telemetry systems based on performance, reliability, power requirements, data rates, and costs and size requirements under relevant borehole conditions including depth, temperature, pressure, type of borehole drilling and completion fluids, and type of formation fluids. In addition, they examined the benefits and drawbacks of various techniques used to place sensors at different depths in the well. A literature review provided information on sensor embedding procedures, reliable data transfer techniques, power supply systems, and preliminary well designs. Borehole telemetry systems were divided into two types: wired and non-wired. The wired systems use physical conduits, such as cables, and optical fibers to communicate sensor measurements from downhole to the surface. Examples of wired telemetry systems are wireline tools, wired drill pipe, and fiber optic systems. Wireless telemetry systems use mud pulses, electromagnetic waves, and acoustic waves in communicating information to the surface.

### Results:

- Wireline telemetry provides high quality information from formations, but not in real time. Wireline has high data rate transmission (greater than 100,000 bit/sec.), but the quality of the log data may be seriously affected by wellbore enlargement. The drilling assembly must be removed from the well to allow the tools to be run in the well, which is time-consuming and costly. Wired drill pipe has high data rates (up to 57,000 bits/s), which allows full seismic waveform transmission in real time, thus increasing safety by reducing the risk of unexpectedly encountering over-pressured zones. Wired drill pipe is expensive, but is appropriate for underbalanced drilling that can be used in complex horizontal wells and for drilling very deep high pressure, high temperature (HTHP) wells when other methods are not available. It can withstand shock and vibration, but has a 350oF temperature limitation. It also requires a reliable data communication method at the tool joint.
- Non-wired, mud pulse telemetry, the most common system used in drilling, is simple to use and provides accurate measurements. However, with its low data transmission rates (~10 bits/s) and the requirement that information must downloaded at the surface, it does not provide data in real-time. The mud pulse systems are not compatible with compressible drilling fluids and cannot be applied for underbalanced drilling applications. The dependence of mud pulse on a continuous incompressible fluid column, high power requirements, and the abundance of moving parts that threaten system reliability, all make mud pulse a poor choice for an ICIF system. Electromagnetic telemetry has a higher data transmission rate (up to 100 bits per second). It is especially suitable for drilling with compressible fluids, thus it is appropriate for underbalanced drilling, near balanced drilling, and managed-pressure while drilling scenarios. However, because of  reliability issues at depths greater than 10,000 feet, its low frequency, and high energy requirements, electromagnetic telemetry may not be a viable option for data transmission over long ranges (such as from very deep wells to the surface). Acoustic telemetry applications are still under testing. The acoustic signal has a very low intensity and discrete frequencies falling into particular bandwidths for filtering drilling noise are required. Signal loss in the drill string increases as the contact between the drill string and borehole wall increases; signal loss in a slanted or horizontal well is expected to be higher than the loss in a vertical well.
- Fiber-optic sensing telemetry uses optical fibers, which transmit light instead of electrons. It has a fundamental advantage in that the fiber serves as both the measurement sensing element and the telemetry channel. Optical fiber has the capability of to carry 10,000 times more information than copper wireline systems. It is very simple to implement, contains no downhole electronics, is cheaper than

## Intelligent Casing-Intelligent Formation Telemetry (ICIFT) System

copper, has greater sensitivity, and is able to transport data over long distances. The system is immune to most environmental conditions, and can tolerate extreme temperatures. It can be permanently deployed outside the production casing. Sensing electronics placed at the surface rather than downhole increases reliability when compared to electrical sensors. Fiber-optic technology offers a wide range of distributed/multipoint sensing: distributed temperature sensing (DTS), distributed strain sensing (DSS), distributed pressure sensing (DPS), distributed acoustic sensing (DAS), and distributed chemical sensing (DCS). In essence, fiber-optic sensing technologies are highly suitable for the development of intelligent permanent well monitoring systems.

- Fiber-optic distributive sensors deployed on the outside of casing combined with radio-frequency identification (RFID) surface acoustic wave (SAW) sensors in the cement can provide economically valuable downhole measurements during casing and early production.
- Researchers proposed several configurations for transmitting data to the surface from sensors deployed outside the production casing. An optical feed-through well head design for casing and tubing hangers would benefit intelligent well systems. Another design would use electromagnetic (EM) and/or ultrasonics methods of communicating through the casing without cutting a feed-through hole in the casing. Ultrasonic techniques and installation of a casing sub in the borehole as part of the production casing were also possibilities.
- ICIF systems can provide downhole measurements at sufficient rates to identify phenomena such as fluid movement and other occurrences that can be mitigated before they become too difficult to manage. Technical and economic benefits include: 1) reduction of well intervention operations, 2) reduction in supervision requirements, 3) performance not affected by weather conditions, 4) permanent well monitoring through the life of the well, 5) early forecasting of well integrity and downhole problems.

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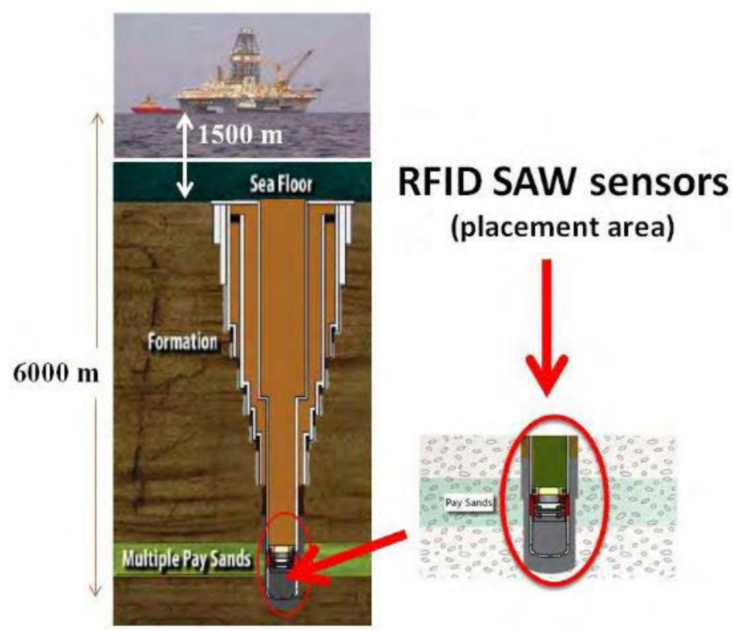
**Period of Performance:** 06/2012-12/2014

Read/download the final report and "Intelligent Casing-Intelligent Formation (ICIF) Design," a paper presented at the 2014 Offshore Technology Conference.




*Scenario for placement of RFID SAW sensors in cement for early detection warning of gas kick during cementing operations.*

## Coil Tubing Drilling and Intervention System Using Cost Effective Vessel

**Objective:** To advance work previously done by designing a cost-effective Coil Tubing (CT) system for down-hole work in deepwater Gulf of Mexico satellite wells, without the need for a Mobile Offshore Drilling Unit (MODU). The enabling technology is a patented self-standing riser that will provide companies with a safe and affordable way to complete, re-enter and maintain subsea wells. Implementation of this system would improve safety and environmental protection, facilitate improved resource recovery from existing satellite wells, and make it practical to develop reservoirs that would otherwise not meet economic hurdles.

**Research Conducted:** Deep water oil and gas production is expensive, and major petroleum companies find smaller deep water fields uneconomical. The development of a sophisticated Self-Standing Riser (SSR) could open up many deepwater (1000 to 5000 ft) shallow gas plays (3000 to 12,000 ft) that are currently evaluated as not commercial using conventional deep water technologies. In addition, SSRs can solve the problem of the abandonment of hundreds of deepwater wells in the Gulf of Mexico, West Africa, and Brazil that need to be re-completed. Recompletion requires costly use of Mobile Offshore Drilling Units (MODU); the cost is prohibitive, and abandonment leaves thousands of barrels of oil in the reservoir.

The group of researchers developed a system that consists of a Self-Standing Riser (SSR), a small (80-120 m) unspecialized monohull vessel, a coiled tubing (CT) spread, and interface packages to connect, deploy and operate these subsystems together. The system concept and design was submitted and progressed through the DNV (technical assurance and assessment) process for qualification of new technology. A candidate well was be identified for a field test. A Joint Industry Project team will be necessary to share in the cost of further detailed design, fabrication and field test of the system.

**Results:**

- During Phase 1 of this follow-on project to RPSEA-Nautilus project 08121-1502-01 (p. 15 of this report), a candidate subsea well was identified and accepted by the operator for a field test. The concept was certified by Det Norska Veritas (DNV) in a study with issuance of a Certificate of Feasibility for the use of the SSR for CT intervention. Phase 2 further developed the design. Detailed requirements for system performance were derived from the desired mission functionality. The extensive set of input data (metocean dynamics, vessel responses, CT loads, and weights) necessary for quantitative dynamic systems analysis was generated. The system properties and numerous performance cases were defined for dynamic analysis. The SSR was simulated and analyzed as a dynamic system for select cases.
- Developed a design for a SSR and supporting equipment suitable for a cost effective vessel to do coiled tubing intervention in ultra-deepwater. There are no remaining significant technology or conceptual gaps; development requires due diligence in industry standard recommended practices for intervention riser systems. The riser enables a full performance envelope of coiled tubing abilities. A successful field test on a deepwater satellite well will prove that a small vessel can operate coiled tubing through an SSR in deepwater, demonstrate improved safety and environmental protection, and incur a cost less than half that of a MODU.
- The team is in the process of establishing an agreement with one or more CT service providers and/or well operators. They will continue qualification of the new technology, complete its detailed design, assist in testing and integrating the system, and make field test preparations for the SSR.

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**Project Number:** 10121-4505-01

**Period of Performance:** 07/2012-12/2014

Additional details on this project are available on the RPSEA website.

## Trident: A Human Factors Decision Aid Integrating Deepwater Drilling Tasks, Incidents, and Literature Review

**Objective:** To design and develop Trident, a Human Factors database and decision aid to help industry practitioners understand and mitigate those aspects of deepwater drilling in which human and organizational performance limitations can result in the failure to meet safety, environmental, productivity, and other system goals.

**Research Conducted:** Human error and human factors are contributing causes in over 50% of well control incidents. While straight-forward cognitive errors and wrong actions contribute to 15% of incidents, even more incidents result from other human factors-related problems including communication failures, workload, management practices, and information availability and presentation problems. These human factors problems increase the risk of mistakes and loss of well control.

The project focuses on identifying Human Factors issues that underlie potentially dangerous situations that can make it difficult to follow procedures and to recover from procedure violations. This project addresses deepwater and ultra-deepwater drilling with both major types of equipment, semi-submersible platforms, and drill ships. Onshore and offshore aspects of drilling operations are also included to ensure a thorough evaluation of deepwater drilling.

In Phase 1, project researchers will conduct a comprehensive Human Factors evaluation of deepwater drilling, including a function-task analysis and a Human Factors assessment of industry accident/incident reports. In Phase 2, the team will conduct a human error analysis of critical deepwater drilling tasks. Results Phase 1 and Phase 2 analysis will be used to develop an integrated Trident database and decision aid. In Phase 3, Trident's value will be demonstrated by using it to evaluate drilling plans, identify Human Factors risks, and design interventions and barriers.

Trident will present human factors information to industry users in a form that is organized, relevant, and easily exploitable by project managers, regulators, intervention developers, and researchers. One likely use would be part of a drilling plan risk assessment and mitigation process where Trident is used to assess and certify plans from a human factors point of view.

The application of Human Factors to deepwater drilling operations is expected to increase personnel safety and enable more efficient and cost-effective drilling operations.

**Results:**

- Developed a database of human factors that included threats and barriers with human factors barriers identified; criticality ratings of barriers for human factors consequence and involvement; and compiled a literature review based on human factors barriers. Analysis of past incidents identified poor communication of risk, delayed response to influx or kick, poor efficiency/thoroughness trade-off decisions (ETTO), and insufficient sensors to support situational awareness as significant factors.

**Ongoing Research:** Trident will be made available via a subscription service to numerous organizations and businesses involved in deepwater drilling. Human Factors consulting services will be offered as part of the subscription. Risk management, insurers, regulators, suppliers, and researchers will benefit from Trident's ability to identify problematic, error-prone tasks and circumstances and to formulate interventions for improving human and system performance.

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**Project Number:** 11121-5101-01

**Period of Performance:** 08/2013-09/2016

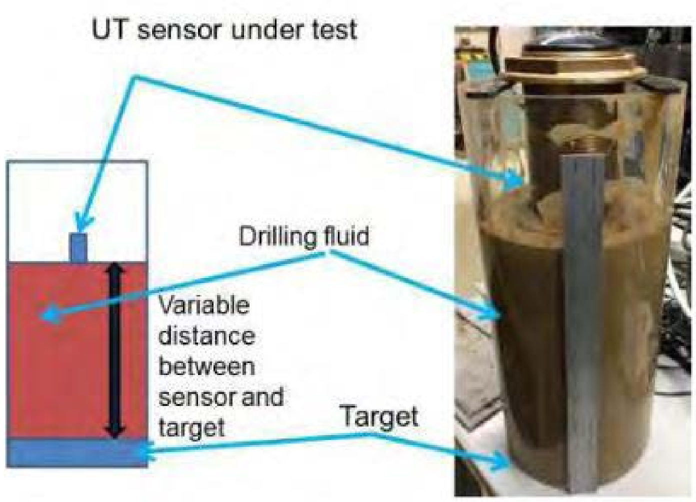
Additional information on this project is available on the RPSEA website.

## Intelligent BOP RAM Actuation Sensor System

**Objective:** To develop a novel auto-compensated sensor system for accurately detecting the presence of drill collars, tool joints and other un-shearable objects in the vicinity of blow-out preventer (BOP) rams and provide feedback to the operator in the event that such an object is detected and assisting the operator with taking corrective action.

**Research Conducted:** In Phase 1, project researchers evaluated various sensing systems and assessed their risks and benefits. Multi-sensor data correlation methodology was developed to address data integrity and mitigate the effect of identified error sources and risks. A down-select process to find a preferred system was conducted. Additionally, mechanical and software integration of a sensor with the BOP was evaluated and the risks were identified and assessed.

For Phase 2, researchers will build on the findings of Phase 1 to develop and test a detailed sensor system prototype. The initial Phase 2 testing will be conducted in a lab-scale test-bed. The sensor system will subsequently be integrated into a simulated BOP structure for further lab testing in a full-scale system to validate the sensing system's capability. Accelerated life testing will also be conducted to assess long term viability of the system, and bring the technology to a field ready development status.




*Ultrasonic proof of concept test rig.*

**Results:**

- A detailed sensor characterization and screening of the technology were conducted in Phase 1. The screening included evaluation of the capability of the sensors to detect change in pipe diameter in the presence of confounding noise source.
- Signal losses in drilling fluids, errors due to pipe movement, and error correction techniques were evaluated using relevant geometries in a lab environment.
- Researchers selected a combined electromagnetic and ultrasonic multi-sensor system for Phase 2 design and testing due to its ability to perform pipe diameter measurement. Both sensing modalities exhibited different sensitivity to errors and noise source. This combined system offers a high degree of robustness in the presence of confounding noise sources.

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**Project Number:** 11121-5503-01

**Period of Performance:** 10/2013-07/2016

Read/download the final report.

## Reliability of Annular Pressure Buildup (APB) Mitigation Technologies

**Objective:** To provide industry with a stochastic tool for analysis, comparison, and choice of possible APB mitigation techniques applicable to an operator's well and field situation.

**Research Conducted:** Annular Pressure Buildup (APB) occurs in all wells with high bottom-hole temperatures, multiple casing strings, and annuli that cannot be vented — which includes most deepwater Gulf of Mexico wells. APB can result in casing string and premature well failure, unless a well is properly designed; APB risks are fully assessed for all load cases; and any necessary APB mitigation methods are evaluated, fully analyzed for effectiveness, and properly implemented.

**Results:**

- Gathered industry feedback via a questionnaire on preferred mitigation strategies. This operator perspective on APB mitigation methods has provided researchers with an ample database of results and allowed them to analyze best mitigation strategies for specific wells.

**Ongoing Research:** The researchers will be compiling their analyses from the industry feedback in a report and using the data to build a screening tool that will help operators identify the best mitigation technique for their well.

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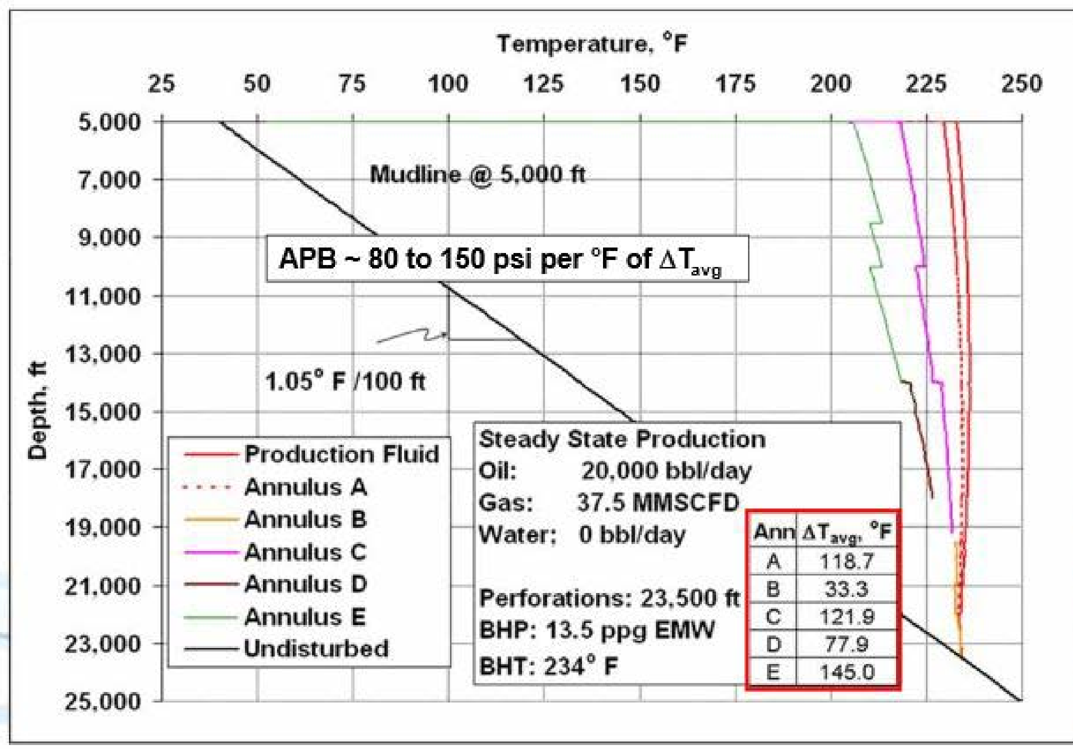
**Project Number:** 12121-6502-01

**Period of Performance:** 07/2014-12/2015

Additional information on this project is available on the RPSEA website.




*Wellbore temperatures.*

# Analysis of Best Practices for Deepwater Cementing in Oil-Based Mud (OBM) and Synthetic-Based Mud (SBM)

**Objective:** To gain a better understanding of what risks are involved with cementing in deepwater using OBMs and SBMs and to develop best practices to decrease the risks.

**Research Conducted:** SBM is often used on offshore rigs because it has the properties of OBM, but its fluid fumes are less toxic than OBM. Further, OBM and SMB are some of the least compatible fluids with cement slurries. Incompatibilities include cross contamination, mud residue in holes, fluid swapping, and other fluid interactions which can result in reduced compressive strength of the cement as well as result in channelling, down-hole gelation, and poor cement bonding.

This study is analyzing the relationship between temperature, pressure, cement bond, degree of mud removal and its effect on zonal isolation in complex well architecture. Fluids under laboratory investigation will include typical commercially available designs of cement slurries, SBM, OBM, and spacer fluids (used to clean residual mud from the wellbore, casing, and formation before cementing operations) with a focus on micro-particulate fluids and other new technologies.

This project will be completed in two phases. The first phase of this investigation is concerned with the chemical reactions between the mud and the cement. In Phase I, there will be a fundamental study of OBM/SBM/cement interactions, modeling of contamination and fluid interchange, and rheological considerations. The results and criteria developed in Phase I will be applied and evaluated in Phase II to candidate wells in three field trials. Phase II will include lab performance testing and large scale testing to evaluate the effectiveness of any applied technology. A working project group of industry representatives will be formed to provide technical review during the course of the project.

Environmental benefits of a successful project include a decrease in contamination, the formation of channels, and improved bonding of cement. Long-term wellbore integrity will be improved and environmental and safety issues such as leaks from the formation and Sustained Casing Pressure will be mitigated. Enhanced integrity of the cement will not only save operators from costly remedial work and additional rig time, but will also increase productivity as well as reduce environmental and safety risks.

**Results:**

- Phase I results are currently being evaluated and a Go/No-go decision will be made regarding Phase II.

**Ongoing Research:** Criteria developed in Phase I is being applied and evaluated to candidate wells in three field trials. Key deliverables of this project include an OBM/SBM contamination study on the fundamentals of OBM/SBM/cement interactions, the development of design criteria for maximum allowable intermixing, the results of field trials, and a comprehensive final technical report.

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**Project Number:** 12121-6503-01

**Period of Performance:** 06/2014-09/2016

Additional information about this project is available on the RPSEA website.

# Characterizing the Behavior of Metal-Based Systems Used for Control Devices in Extreme Environments

**Objective:** To study failure mechanisms of critical metal components in simulated ultra-deep well environments for drilling, completion, and production applications. By understanding the environmental and mechanical factors that affect component service life, these failures can be mitigated.

**Research Conducted:** At present, publicly available data about the performance of critical metal components under extreme offshore conditions is limited. Therefore, it is of utmost importance to improve industry understanding of how the ultra-deep environments affect the service life of components and use this knowledge to develop cost-effective failure mitigation methods.

To determine the behavior of materials under extreme conditions, the research focused on understanding and documenting the effects of both the mechanical stress state and the environmental interactions, general and localized corrosion, and their role in the corrosion-fatigue processes.

The project is part of the Wellbore Integrity – Improved Science Base of Materials program that is also focused on improving the science-base for foam cements and evaluation of the "lithology: cement: casing" barrier integrity under ultra-deep water subsurface conditions.

Researchers are conducting a number of different studies to provide accurate information on improving understanding of how conventional and advanced alloys and their surface treatments may allow for safe and reliable operations in extreme and unproven wellbore conditions. These studies include:

- The Offshore REliability DAtabase (OREDA) was used to identify possible research areas. OREDA compiles information on oilfield equipment classes, subunits, and maintainable items, and utilizes a failure rate function to predict the likelihood that a component will fail within a specified period of time. Failure mode effects and criticality analysis (FMECA) methodology was reviewed to determine if FMECA can be applied to an example offshore system (e.g., topside of an offshore platform or a subsea installation) using the OREDA data. In addition, an expert survey of personnel who manage OREDA was conducted to glean knowledge on how materials related failures are identified across disciplines in the offshore industry.
- Corrosion and Fatigue of Hammer Peened and Heat Treated Oil Grade Alloy 718 involved examination of the microstructures developed as a consequence of the hammer peening surface modification procedure, and changes due to subsequent heat treatment to improve bulk mechanical properties. In addition, fatigue crack growth rate and corrosion-fatigue crack growth rate studies of the various microstructures, and comprehensive electrochemical investigations were performed.
- Characteristics of Fracture in UD-165 Drill Pipe after Simulated Sour Service investigated mechanisms of cyclic stress crack propagation using scanning electron microscopy, x-ray diffraction, and energy dispersive x-ray spectroscopy, and wave-length dispersive x-ray spectrscopy. Fatigue test under cyclic stress were performed on pre-cracked samples in a dearated 5% NaCl solution at 20°C buffered with $CO_2$/$Na_2CO_3$ for pH=7 or $Na_2CO_3$/$NaHCO_3$ for pH=9 or 12 and in contact with $H_2S$. The partial pressure of $H_2S$ ($pH_2S$) was 0.83 kPa (0.12 pounds per square inch [psi]) and 8.3 kPa (1.2 psi), respectively. These solution types are is used by the industry to simulate a generic production fluid.
- Catalytic Properties of $H_2S$ in Corrosion Degradation of High-Strength Steels used thermodynamic modeling and electrochemical methods to understand the possible mechanism involved in sour corrosion. The OLI electrolyte chemistry simulation software was used to model chemical corrosion and how varying the concentrations of HCl and NaOH in a solution changes the pH. Corrosion rates of S-135 and UD-165 in deaerated 5% NaCl solution buffered with $NaHCO_3$/$Na_2CO_3$, in contact with $H_2S$ were determined using direct current polarization, electrochemical impedance spectroscopy, linear polarization resistance, and electrochemical frequency modulation methods.
- Role of Yield Strength and Microstructure on Fatigue Crack Growth (FCGR) Rate in Sour Environments aimed at understanding and quantifying the effects of yield strength on the FCGR, as well as the response between yield strength and fracture toughness. The research concentrated on controlled testing of newer line pipe steels; results were compared against the historical data to evaluate the FCGR performance of various line pipe grade steels in sour environments.

# Characterizing the Behavior of Metal-Based Systems Used for Control Devices in Extreme Environments

- Development of Electrochemical Sensors to Monitor Corrosion Performance in Risers and Other Subsea Structures was concerned with selecting materials and designing reference electrodes. The design of the reference electrodue included an analysis of working parameters of commercial solid state reference electrodes for their use in synthetic seawater and sour brine solutions for pressures up to 150 bar and temperatures up to 150°C.

## Results:

- A full accounting of technical results from this project and others in the Offshore Portfolio are available at https://edx.netl.doe.gov/offshore including publications, presentations, datasets, tools, and other relevant information. This resource is updated quarterly and reflects publically available results from this project and the portfolio as a whole.
- OREDA and FMECA. A FMECA analysis was applied to a piece of equipment used in offshore technologies using OREDA data. Specifics on mechanisms of the materials-related failures for the components within the equipment are not available. However, the analysis demonstrated how FMECA could be used, with additional information, in directing offshore materials research. The survey of OREDA experts was generically designed to probe the interviewees' knowledge and opinion of the significance of materials used in subsea structures and components by the offshore industry. Expert surveys provided feedback on specific systems and materials related issues in offshore equipment. Concerns largely stemmed from reliability issues such as 1) effective detection and evaluation of degraded systems prior to a major event, and 2) the behavior of materials in more extreme, harsher, and or changing conditions.
- Corrosion and Fatigue of Hammer Peened and Heat Treated Oil Grade Alloy 718. The corrosion-fatigue crack growth results showed no obvious effect of 3.5 wt% NaCl solution on the crack growth rates of oil-grade alloy 718 in the three different aged conditions. However, crack growth rate increased in a 21 wt% NaCl for all specimens. Crack growth rate differences were more pronounced in the lower ΔK regions where the effects of stress and strain on the crack tip are less dominant. Aging treatments led to lower corrosion-fatigue crack growth rates of oil-grade alloy 718 in all tested condition. Scanning electron microscopy of the fracture surfaces revealed that the cracks propagated transgranularly.
- Electrochemical test results showed that machine hammer peening has a beneficial influence on the pitting corrosion resistance of oil-grade alloy 718 in a 3.5 wt% NaCl solution, as indicated by a significant increase of the critical pitting potential (+134 mV), accompanied with lower corrosion current density and higher polarization resistance.
- Surface smoothing (the generation of a larger compressive residual stress in the near surface region and the formation of nano-grains and nano-twins produced by the surface modification treatment) improved the pitting corrosion behavior of oil- grade alloy 718 in a 3.5 wt% NaCl solution. A two-step aging treatment resulted in higher susceptibility to pitting corrosion in a 3.5 wt% NaCl solution at RT. This was manifested as a significant decrease in polarization resistance and critical pitting potential. However, the hammer-peened specimen, processed at the higher feed rate (4 m/min) and followed by aging treatment, showed the best pitting corrosion resistance of the aged surface-treated samples.
- The improvement in pitting corrosion behavior of oil-grade alloy 718 in a 3.5 wt% NaCl solution at RT was mainly attributed to surface smoothing and the larger compressive residual stress left after the aging treatment. Fracture toughness (FT) of oil grade 718 is significantly impacted by the environment, more so than the fatigue crack growth rate (FCGR) behavior. As such Custom Age 625+ may be the better alloy for sour service and severe sour service.
- Characteristics of Fracture in UD-165 Drill Pipe after Simulated Sour Service: The UD-165 sample after the fatigue experiments failed catastrophically after exposure to the pH=7 solution. In the pH= 9 solution, the crack propagated intergranulary and transgranulary. A few secondary cracks were observed near the crack tip. In some areas, energy dispersive spectrographic (EDS) analyses detected high concentrations of iron (~70%) and 1 sulfur (~20%). Fe- and S-rich corrosion products did not impede diffusion of hydrogen to the crack tip; fatigue crack propagation was controlled by hydrogen diffusion. In the pH=12 solution, the crack tip became plugged with Fe and S-rich corrosion products, which indicates crack propagation was not affected by $H_2S$. Fatigue crack propagation appeared to be controlled by stress corrosion cracking.

## Characterizing the Behavior of Metal-Based Systems Used for Control Devices in Extreme Environments

- Catalytic Properties of $H_2S$ in Corrosion Degradation of High-Strength Steels: Thermodynamic simulations were used to assess the effects of changing environments on sulfide-assisted corrosion mechanisms. The first series of thermodynamic simulations and experimental results showed the following:

1. The concentration of dissolved $H_2S$ depends greatly on partial pressure of $H_2S$.
2. The concentration of $HS^-$, which is the primary dissociation product of $H_2S$, increases with increasing $H_2S$ partial pressure and solution pH.
3. Increasing pH up to 12.3 generally decreased the corrosion rates at steady state regardless of partial pressure of $H_2S$. Several testing conditions showed that corrosion rate was the highest at pH 10.5.
4. Surface analysis results indicate the corrosion product generally changed from iron sulfides to iron oxide as pH increased, which agrees with Pourbaix diagram for $Fe-H_2O-H_2CO_2-H_2S$ 69 kPa system.

- Role of Yield Strength and Microstructure on Fatigue Crack Growth (FCGR) Rate in Sour Environments. Controlled testing of newer line pipe steels results compared against the historical data to evaluate the FCGR performance concluded the following:
  - FCGR of all grades of line pipe steels increases with decreasing frequency and reaches a plateau for the X52, X65, and X80 grades. This suggests that FCGR propagation in all of the line pipe steels is associated with a hydrogen driven mechanism. No plateau was observed for X100 and 4137M grades, and was likely due to K 1SSC behavior.
  - The plateau FCGR appears to be independent of the yield strength at the ΔK=1000 Nmm-3/2 in the mildly sour environment. At a higher value of ΔK, 1211Nmm-3/2, FCGR decreases with increasing yield strength.
  - The effect of yield strength at the higher ΔK appears to be associated with the shorter diffusion distances in the higher strength steels, coupled with the higher hydrostatic stresses which enhance the concentration of hydrogen.
  - The X-52 vintage pipe had the coarsest grain size and exhibited almost complete transgranular crack propagation during the fatigue test. The newer X-52 and the X-65 pipe steels had a finer ferritic/bainitic microstructure and showed some signs of transgranular crack propagation. The X-80 steel was predominantly bainitic with acicular grains.
  - Local misorientation maps showed a qualitative increase in plasticity around the crack with a corresponding increase in yield strength from X-52 vintage to X-80. Transmission electron microscopy imaging of the region close to the fracture surface shows dislocation sub-cell formation as well as significant dislocation activity. Increased mobility of dislocations due to the presence of hydrogen would be consistent with this observation.
- Development of Electrochemical Sensors to Monitor Corrosion Performance in Risers and Other Subsea Structures: Multiple copper sulfate electrodes (CSE) were tested in the temperature range of 20 to 150°C at 30 bar versus 1 mol/kg KCl(aq) Ag/AgCl reference electrode. It was found that the electric potential difference between these two electrodes was repeatable for the conditions tested. Theoretical modeling using existing extrapolated thermodynamic data was used to model the expected electric potential difference; it was found that the electric potential difference between these two electrodes match closely with theoretical modelling from 20 to 100°C but started to deviate above 100°C. Overall, results indicate that this design of the CSE electrode appears to be a promising candidate for an elevated temperature and pressure reference electrode.

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### Project Number: Task 2

### Period of Performance: 05/2010-09/2015

## Improving Science-Based for Wellbore Integrity, Foam Cements

**Objective:** To compare physical and chemical tests of commonly used offshore foamed cements at in-situ versus atmospheric conditions to improve understanding of the integrity and longevity of foam-cements.

**Research Conducted:** Cementing is one of the crucial steps in drilling safely for oil and natural gas. Cement, in general, is used to protect the wellbore from dangerous influxes of formation fluids and protects the shallow groundwater environment. The properties of the cement are important not only at the time of placement, but for many years after abandonment; it is one of the very important elements on which wellbore integrity is evaluated, and one on which risk is assessed.

Foamed cement is a combination of cement slurry, gas (commonly nitrogen), and a foaming agent. It has properties uniquely suited to deep drilling applications, such a strength, ductility, low density, stabilizes at high temperatures. At present, knowledge of foamed cements, most commonly used in deep offshore wells, is largely limited to laboratory studies at atmospheric conditions.

Research includes a combination of laboratory-based experimental and characterization studies, integration and interpretation of field-based datasets, and development and application of numerical simulators. In addition, this project will assess the state of knowledge about the performance and integrity of cements in offshore Arctic settings to identify key performance knowledge gaps for future R&D.

Researchers are conducting a number of different studies and experiments in order to provide accurate information on foamed cements that relate to potential risks, and to improve safety. These include:

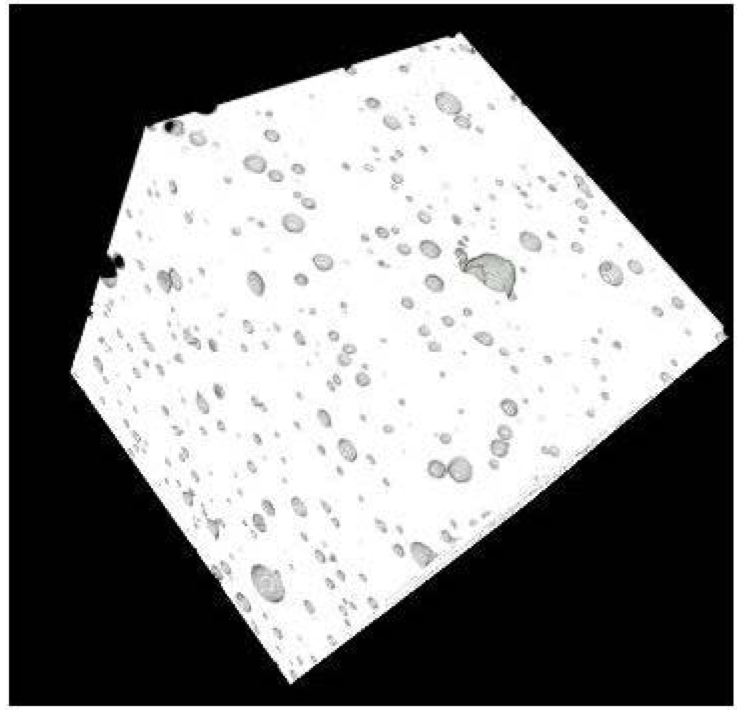
- Experimental evaluation of foamed cement systems: This research examines foamed cement stability at various depths and in-situ pressures. Results are to be correlated with the current method of atmospheric testing as outlined in API RP 104-B. Researchers are using NETL's industrial computed tomography (CT) imaging scanner to provide bubble size distribution and 3D image datasets of (1) atmospheric foam generated with the current test method across a range of foam qualities; and (2) laboratory generated foamed cement under pressure across a similar range of foam qualities. Smaller samples may be evaluated using the micro CT-scanner providing even greater resolution.
- Modeling spatial distribution of gas bubbles in foamed cement systems: Researchers are interested in how the spatial distribution of gas bubbles in cement foams affects the mechanical properties and failure probability of the as-set foam cement. The challenge is how to transfer knowledge of the bubble distribution at laboratory conditions to field conditions at depth, where overburden pressures decrease the gas fraction in the foamed cement. Modeling efforts are taking into account (1) variable gas volume fraction with depth/pressure, (2) time dependent non-Newtonian rheology of the suspending phase as the hydration reaction proceeds in the suspending cement phase, and (3) interplay during shear flow between the local flow profile, emergent coarse-grained rheology of the cement/gas bubble composite, and spatial correlations between bubbles and bubble motion (bubble entrainment, shear-induced bubble rearrangements, etc.).
- Geophysical properties of foamed cement systems: Researchers are measuring the acoustic properties (P/S1/S2 wave velocity) of wellbore cement systems over a range of relevant pressures in order to understand the change in properties from a seismic wave propagation perspective. The work includes measuring porosity, permeability, and ultrasonic velocity measurements using a NER AutoLab 1500 in the NETL Core Flow Lab. Core-scale velocity measurements allow researchers quantify the physical properties of various foamed cement systems at different wellbore conditions. CT images of samples are being used to match saturation distribution to velocity measurements.
- Foam destabilization: This area of research addresses the observation that bubble migration and coalescence continue to occur during setting of foamed cement; the bubble size distribution changes are due to foam destabilization after movement has ceased. Fresh foamed cement samples are being CT-scanned several times during set-up. Time-lapse scans will be compared to measured mechanical properties of the foamed cement samples to provide insight into mechanisms that influence foamed cement stability.

Additional activities planned under this task include: (1) working with industry to develop the next phase of foamed cement testing and report on a planned path forward and impacts on industry to date, and (2) evaluating and reporting on the state of knowledge and potential technology gaps related to Arctic offshore cement.

## Improving Science-Based for Wellbore Integrity, Foam Cements

### Results:

- A full accounting of technical results from this project and others in the Offshore Portfolio are available at https://edx.netl.doe.gov/offshore including publications, presentations, datasets, tools, and other relevant information. This resource is updated quarterly and reflects publically available results from this project and the portfolio as a whole.
- Examination and comparison of foamed cement generated using atmospheric methods and foamed cement generated in the field revealed an unexpected discovery: foamed cement generated under the current American Petroleum Institute (API) protocol using atmospheric methods look nothing like those generated in the field. Significantly smaller bubbles and lower permeability are observed in the field-generated samples. Mechanical testing is underway in an effort to relate CT bubble-size distribution to mechanical properties. Flow and pressure induced changes in foamed cement structure may cause significant changes in the cured cement properties.
- Numerical models are being utilized to determine wellbore conditions under induced shear; simulations at the wellbore scale are underway to understand and predict the properties of the foamed cement in the well. Work is continuing to isolate flow, distribution, and other relevant properties that can be engineered into safer and more efficient placement of foamed cement



*CT-image of a foam cement sample generated at NETL for bubble size distribution analysis.*

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**Project Number:** Task 3

**Period of Performance:** 05/2014-09/2015

## Risk Reduction at the Drill Bit — Adaptation of Existing Technology to Reduce Risks Associated with Deep and Ultra-Deep Drilling

**Objective:** To adapt existing technology and data to enable development of an early detection system for over-pressured formations; the goal is to detect conditions just after the drill penetrates the formation and causes a kick, but before that kick ascends to the rig floor.

**Research Conducted:** During drilling, drilling muds are used to cool the bit, flush cutting from the well bore, equalize pressure between the formation and wellbore, and seal off porous rock layers. When the drill bit unexpectedly encounters formation fluids and the drilling mud cannot balance the increase in pressure, oil, natural gas, and/or water flow into and up the wellbore, annulus, and drillpipe. This is called a kick. Large amounts of fluids under high pressures can escalate the kick into a blowout when they reach the surface if recognition of the situation is delayed and blowout preventers are not closed in time. Blowouts endanger the site infrastructure, environment, drilling rig, and most important, the people. Commonly, an increase in drilling rate and the rate of mud return signals the kick, but the time delay can result in loss of well control.

This task builds on results of Phase 1 work conducted under the EPAct Ultra-Deep Water Portfolio. Numerical and experimental validation is utilizing borehole and field datasets through analysis and development of new reprocessing techniques.

### Results:

- A full accounting of technical results from this project and others in the Offshore Portfolio are available at https://edx.netl.doe.gov/offshore including publications, presentations, datasets, tools, and other relevant information. This resource is updated quarterly and reflects publically available results from this project and the portfolio as a whole.
- Phase 1, a proof of concept work completed earlier this year, established the goal of developing a low cost process that determines if formation fluid influx (kick) has occurred while drilling a well. Specifically, the report evaluated the mathematical filtering algorithms needed to separate intra-borehole data from geophysical well log measurements in support of rapid kick detection. The report also compares the rate of data transfer from the bottom of the wellbore to the rig floor with the rate of physical information reaching the well bore over various subsurface depths.
- Despite current bandwidth limitations, electronic data transfer rates are almost instantaneous relative to the physical kick rise rate, which can take up to several minutes.
- A new method using measurements that are made as part of the standard well logging instrumentation suite was developed. It has received a provisional patent and has been accepted for full patent consideration by NETL's Invention Review Board.

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**Project Number:** Task 7

**Period of Performance:** 05/2014-09/2015

## Evaluation of Lithology: Cement: Casing Barrier Integrity under UDW Subsurface Conditions

**Objective:** To study the interactions between wellbore materials that may lead to catastrophic failure of the well over time.

**Research Conducted:** Cementing problems and casing corrosion are two major factors attributed to the loss of wellbore integrity in deep offshore wells. Wells drilled in extreme environments of the Arctic and of the ultra-deep Gulf of Mexico are subjected to cyclic changes in pressure and temperature that can compromise the cement bond and allow caustic fluids to corrode the cement and casing. In addition, these environments are characterized by narrow fracture gradients, corrosive reservoir fluids, poorly consolidated formations, and the presence of hydrates or permafrost. The cement and well casing must be designed withstand these conditions over the life of the well.

The research is designed to determine the capability of wellbore materials to function properly in extreme conditions. It consists of 5 areas of investigation.

1. A report focusing on the role that Arctic conditions and extreme deep-water environments play on wellbore integrity and zonal isolation. Corrosion along the casing/cement interface, wellbore integrity along the cement/formation interface, and mudcake development and removal along the wellbore, and the effects of stress cycling are being studied. This report lays the foundation for identifying and prioritizing research needs.

2. Corrosion behavior of casing material that is actively protected by Ordinary Portland Cement. With new alloys being developed it must be ensured that cement, which is used to protect casing material, does not have a delirious effect on the casing metal.

3. Corrosion behavior of casing material when the cement has lost its ability to buffer acidic and corrosive fluids. The mechanism for how corrosive fluids might attack exposed casing material must be understood in environments characterized by highly corrosive fluids with the potential to rapidly develop conduits.

4. The impact of stress loading-unloading cycles on the casing/cement and cement/formation interface. Loading cycles can lead to failure via tensile fractures or micro-annulus debonding along the interface. This can lead to pathways for fluids to leak into overlying formations or allow corrosive environments to reach the casing strings.

5. Inadequate bonding along the cement/formation interface due to remnant mudcake and complex formations (poorly consolidated, tight fracture gradients, presence of hydrates or permafrost). Inadequate bonding can lead to the development of channels that allow the flux of fluids into overlying formations.

The first set of experiments are studying the role of mudcake development and removal and the formation of channels along the cement/formation. The second set of experiments used a scaled wellbore model to apply stress loads to observe micro-annulus debonding along interfaces using X-ray Computed Tomography. Finally, a Finite Element Model is being developed to use experiment observations to study material behavior at extreme conditions.

### Results:

- A full accounting of technical results from this project and others in the Offshore Portfolio are available at https://edx.netl.doe.gov/offshore including publications, presentations, datasets, tools, and other relevant information. This resource is updated quarterly and reflects publically available results from this project and the portfolio as a whole.

- Cement degradation measurements were carried out and a pure cement-simulated pore solution (CSPS) was determined for Class H cement exposed to 10 MPa $CO_2$ in 5 mass % NaCl brine at 100°C. CSPSs are used to avoid the long exposure time required for testing materials exposed to chlorides in concrete.

- Experimental corrosion behavior of casing material using L-80 casing: L-80 casing material was exposed to a CSPS at high pressure high temperature (HPHT) using electrochemical methods. Average corrosion rate determined by linear polarization resistance and electrochemical impedance spectroscopy for L-80 was on the order of 0.1 mm/y. Electrochemical parameters indicate that the kinetics of corrosion process is controlled by a chemical step in the anodic reaction. The kinetic limitation for the anodic reaction may have been due to a weakly protective passive film or a kinetically slow chemical intermediate step in the dissolution mechanism. No significant change in the corrosion behavior of L-80 in CSPS was observed between stirred and unstirred conditions indicating that ion diffusion does not play a role in the material degradation. Corrosion evalua-

## Evaluation of Lithology: Cement: Casing Barrier Integrity under UDW Subsurface Conditions

tion of L-80 in CSPS containing $H_2S$ was initiated. Design of the L-80 sample was completed and the first set of the samples machined. Also, a cement sample was designed for obtaining CSPS. An electrochemical setup was assembled for carrying out corrosion tests in CSPS representative of cold-climate environments.

- Impact of stress-loading and unloading: A wellbore geomechanics model is under development. Matlab is being used for the coding of a simple analytic solution for the stress distribution around a cemented annulus. This will serve as a simple test case for numerical simulations to validate the base case for a more sophisticated model developed in COMSOL, a multiphysics simulation platform. A code to transform tectonic stress regimes (normal, thrust, strike-slip) into boundary conditions for a deviated wellbore has been developed. This is required to transform actual field stresses to the simplified coordinate system required for COMSOL.
- X-ray computed tomography: In the proof-of-concept experiment, the X-ray CT system successfully imaged a scaled-down wellbore sample. The metal components did not provide sufficient noise or beam attenuation to affect data quality. An increase in confining stress caused cracks in the surrounding Berea Sandstone which may be considered as potential leakage pathways.

**Ongoing Research:** Engineering design for the wellbore apparatus and control software using NI LabVIEW is under development.

Researchers will also continue exploring applications of Computed Tomography method for detecting internal cracks and voids in metals. If successful, the CT will be used for revealing nondestructively cracks and voids at a casting/ cement interface caused by corrosion processes.

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**Project Number:** Task 8

**Period of Performance:** 04/2014-09/2015

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